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THE MANGANESE MINERALS: THEIR IDENTIFICATION AND PARAGENESIS.

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INTRODUCTION.

THIS paper is devoted to a study of the following problems:

1. Methods for the mineralographic determination of the opaque manganese minerals.
2. A microscopic study of the internal structure of each of the opaque manganese minerals.
3. The textural relationships of the manganese minerals to each other, and to the iron oxides, as seen in polished sections; with special reference to the manganiferous iron ores of the Cuyuna Range.

DETERMINATIVE METHODS FOR THE IDENTIFICATION OF MANGANESE MINERALS.

TABLE I.

OPAQUE MANGANESE MINERALS AND THEIR CHIEF PROPERTIES.

Name.	Formula.	Per Cent. Mn.	Combined Oxygen.	Specific Gravity.	Hardness.
Oxides:					
Manganosite.....	MnO	77.46	22.54	5.18	5–6
Manganite.....	$Mn_2O_3.H_2O$	62.50	27.27	4.2–4.4	4
Polianite.....	MnO_2			4.8–5	6–6.5
Pyrolusite.....	MnO_2	63.22	36.78	4.7–4.8	2–5
Hausmannite.....	Mn_3O_4	72.05	27.95	4.7–4.8	5–5.5
Braunite.....	$3Mn_2O_3.MnSiO_2$	63.59	26.43	4.7–4.8	6–6.5
Psilomelane.....	$4MnO_2$(Mn, Ba, K, Co, Ni)O	67.35	32.65	3.7–4.7	5–6
Wad.....	Mn. oxides			3–4	1–5
Bixbyite.....	$FeO.MnO_2$			4.95	6–6.5
Pyrophanite.....	$MnO.TiO_2$			4.54	5–6
Senaite.....	$(Fe, Pb)O_2(Ti, Mn)O_2$			4.7–5.3	6
Dysluite.....	$(Zn, Fe, Mn)O(Al, Fe)_2O_3$			4.6	5–5.8
Franklinite.....	$(Fe, Zn, Mn)O(Fe, Mn)_2O_3$			5.0–5.2	5.5–6.5
Jacobsite.....	$(Mn, Mg)O.(Fe, Mn)_2O_3$			4.75	6
Chalcophanite....	$(Mn, Zn)O.2MnO_2.2H_2O$			4	2.5
Sulphides:					
Alabandite.....	MnS			4	3.5–4
Hauerite.....	MnS_2			3.46	4
Tungstates:					
Wolframite.....	$(Fe, Mn)WO_4$			7.2–7.5	5.5
Hübnerite.....	$MnWO_4$			7.2–7.5	5.5
Tantalates, etc:					
Columbite and Tantalite.....	$(Fe, Mn)(Nb, Ta)_2O_6$			5.3–7.3	6

The writer wishes to express his thanks to members of the United States Geological Survey, especially Mr. D. F. Hewett, who has been most generous in offering materials for the investigation; to Dr. William E. Ford, of Yale University, for selected ore specimens; to Dr. W. H. Emmons, Dr. F. F. Grout, and Dr. G. M. Schwartz, of the Department of Geology of the University of Minnesota, for helpful suggestions and criticisms; to Mr. Frank Krey for unpublished information regarding the stratigraphy of the Cuyuna Range.

Because of the close relationship of iron and manganese, isomorphous minerals are common and the determination of such minerals can be accomplished only by complete analyses. However, a study of polished specimens gives much information on intimate mixtures of oxides in which the grains are not submicroscopic in size.

TABLE II.

ANALYSES OF SOME OF THE MINERALS USED FOR DETERMINATION OF MICROCHEMICAL REACTIONS. G. A. Thiel, Analyst.

A. Pyrolusite.

	I.	II.	III.	IV.	Theoretical Composition.
MnO_2.....	94.43	96.20	78.04	96.53	100.00
H_2O.....	1.72	1.21	1.36	1.70	
SiO_2.....	nd.	2.01	19.31	1.03	
Fe_2O_3.....	2.52	nd.	nd.	.23	
	98.69	99.42	98.71	99.49	100.00
Total Mn....	59.43	60.87	49.43	61.04	63.22
Sp. G.....	4.783	4.776	4.682	4.824	4.7–4.8
H.....	2	2.5	3	2.5	2–4

I. Pyrolusite, Mangan mine, Cuyuna Range. Group of soft radiating needles; structure similar to manganite. Polished surface shows small amount of limonite.

II. Pyrolusite, Phillipsburg, Mont. Specimen from Pardee collection of U. S. Geol. Survey. (See Bull. 725, p. 164.)

III. Prismatic needles of pyrolusite, Crimora mine, Va. Polished surface shows finely granular quartz between the grains of pyrolusite.

IV. Pyrolusite. Specimen No. 518, Mineralography collection, University of Minnesota. Origin unknown.

The minerals used in determining the microchemical reactions given in the determinative tables of this paper were analyzed and the physical properties and chemical compositions determined. Volhard's permanganate titration was used for the determination of manganese and the combined water of the hydrous oxides was determined by the closed tube method.

B. Manganite.

	I.	II.	III.	IV.	V.	Theoretical Composition.
Mn_2O_3.....	88.27	86.79	85.11	82.12	88.69	89.77
H_2O.....	10.10	10.30	10.25	10.21	9.87	10.23
Fe_2O_3.....	nd.	nd.	nd.	5.72	nd.	
SiO_2.....	nd.	nd.	4.13	nd.	1.20	
BaO.....	nd.	1.83	nd.	nd.	0.00	
	98.37	98.92	99.49	98.05	99.76	100.00
Total Mn...	61.33	60.50	59.34	57.17	61.76	62.50
Sp. G.....	4.439	4.413	4.341	4.372	4.243	4.2–4.4
H.....	4	4.5	4	4.5	4.5	4–5

I. Manganite, radiating group of needles. Nova Scotia.

II. Manganite, prismatic crystals in a barite gangue. Harz Mountains, Germany.

III. Massive manganite composed of small groups of radiating needles, with a few microscopic grains of quartz. Minas Geraes, Brazil.

IV. Porous manganite ore, Mangan mine, Cuyuna Range.

V. Wedge-shaped manganite crystals from a quartz-manganite vein. Mahnomen pit, Cuyuna Range.

C. Braunite.

	I.	II.	III.	IV.	Theoretical Composition.
Mn_2O_3.....	62.17	65.59	60.09	69.36	67.51
MnO.....	20.58	18.35	16.80	19.40	22.51
SiO_2.....	13.23	14.61	8.17	9.27	9.98
Fe_2O_3.....	3.11	nd.	nd.	nd.	
BaO.....	nd.	nd.	8.38	1.33	
	99.09	98.55	93.44	99.36	100.00
Total Mn...	58.46	59.32	54.32	62.70	63.59
Sp. G.....	4.793	4.782	4.693	4.813	4.7–4.8
H.....	6	6	6	6	6–6.5

I. Braunite, small octahedral crystals. Langban, Sweden. Polished surface shows remnants of a brown silicate gangue. No other manganese minerals present.

II. Braunite, Jakobsberg, Sweden. Specimen contained several small quartz grains that were evident only in polished surface.
III. Braunite crystals in a barite gangue. Harz Mountains, Germany.
IV. Braunite, large crystals in barite, Ilefeld, Germany.

D. Hausmannite.

	I.	II.	III.	Theoretical Composition.
Mn_3O_4.....	97.48	95.95	97.19	100.00
H_2O.....	1.21	Trace	0.00	
SiO_2.....	Trace	.36	1.74	
BaO.....	.43	CaO...2.43	nd.	
	99.12	98.74	98.93	100.00
Total Mn...	69.37	69.12	70.03	72.05
Sp. G.....	4.782	4.764	4.814	4.7–4.8
H.....	5.5	5.5	5	5–5.5

I. Hausmannite, Batesville district. Speciment No. B33, U. S. Geol. Survey collection. Polished surface showed a few very small grains of psilomelane.
II. Hausmannite, Ilmenau, Thuringia. Contained a few microscopic grains of calcite.
III. Hausmannite, Langban, Sweden. Finely granular quartz between crystals.

E. Psilomelane (Manganous Manganate).

	I.	II.	III.
Mn_2MnO_5...	73.95	75.30	74.69
Fe_2O_3.....	2.41	3.12	2.94
CaO.....	.34	1.78	2.11
Na_2O.....	.09	.07	.08
K_2O.....	.10	.44	.23
BaO.....	14.78	8.12	11.34
H_2O.....	5.36	4.64	7.52
	97.03	93.47	98.81
Total.....	49.82	51.20	50.67
H.....	6	6.5	6

I. Concretionary psilomelane, Walnut Grove, Ga.
II. Massive concretion of psilomelane, near Lead, S. Dak.
III. Psilomelane nodule, Portsmouth pit, Cuyuna Range.

Notes on the Reagents Used.—Most of the oxides of manganese are chemically inert with the reagents suggested in the determinative tables that have been published for the identifica-

tion of opaque ore minerals.[1] Therefore the writer was obliged to develop a series of microchemical and mineralographic tests by means of which the opaque manganese minerals could be differentiated. Davy and Farnham have pointed out that detailed descriptions of the way in which microchemical reactions proceed are in many cases valueless because of the fact that two specimens of the same mineral do not always yield exactly identical results, but comparative results are of value. In the case of manganese minerals this is especially true, for in some of the oxides even the crystallographic orientation of the polished surface means variations in appearance when subjected to reflected light. Yet by the use of various strong reducing and oxidizing agents, it is possible to distinguish the oxides even where intimate mixtures occur.

The following reagents, in addition to those used by Davy and Farnham[2] are useful for work on manganese minerals. A few others for special diagnoses are mentioned in the text.

1. Stannous chloride—saturated solution.
2. Hydrogen peroxide—commercial.
3. Sulphuric acid—concentrated.
4. Hydrochloric acid—concentrated.
5. Gold chloride, 1 gm. per liter distilled water.
6. Potassium carbonate and potassium nitrate.[3] (Equal parts of a saturated solution of each.)

1. Stannous chloride, prepared by dissolving tin in concentrated HCl, was chosen because of its properties as a strong reducing agent. Characteristic etchings are produced in a short time.

2. Hydrogen peroxide. The catalytic decomposition of hy-

[1] Campbell, W., "The Microscopic Examination of Opaque Minerals," ECON. GEOL., vol. 1, p. 759, 1906.

Murdock, J., "Microscopical Determination of the Opaque Minerals," John Wiley and Sons, 1916.

Davy-Farnham, "Microscopic Examination of the Ore Minerals," McGraw-Hill Book Company, 1920.

[2] *Op. cit.*

[3] Brommal, A., "Same Microchemical Methods," *Geol. Mag.*, 1920, p. 123

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drogen peroxide by MnO_2 has long been recognized by chemists.[4]

It is at once evident that porous and powdered substances greatly accelerate the evolution of oxygen because of the greater free surface exposed. Therefore, amorphous oxides, as psilomelane, wad, and pyrolusite, produce a violent effervescence even on polished surfaces, whereas iron oxides are all negative.

5. Gold chloride. Various manganese minerals associated with different carbonate and silicate gangues were subjected to a treatment with a gold chloride solution. The polished surfaces were suspended for twenty-four hours in a dilute solution containing 1 gm. of gold chloride per 1,000 cc. distilled water. The specimens were allowed to dry and were examined with a reflecting microscope. A thin yellowish-brown film of metallic gold and manganese oxide was precipitated on the grains of the softer amorphous oxides, such as pyrolusite and wad. This reaction is not specific in the presence of carbonaceous material. More concentrated solutions of the gold chloride were avoided because of the tendency of the precipitate to overlap neighboring minerals that did not themselves precipitate gold.

The reaction of gold chloride is limited to psilomelane, pyrolusite, and wad. Crystals of braunite, hausmannite, manganite, and manganosite, together with crystalline ores of these minerals do not take the gold from solution in amounts that can be detected on polished surfaces. Amorphous hausmanite, however, reacts like pyrolusite. The amorphous hausmanite was produced by the conversion of any of the other non-crystalline oxides into Mn_3O_4 by roasting.

In the determinative tables given below, the outline of Davy and Farnham's text for the microscopic examination of ore minerals is followed and elaborated.

[4] Ostwald, Wm., "Principles of Inorganic Chemistry," MacMillan and Co., p. 162.

TABLE III.

KEY OUTLINE OF THE DETERMINATIVE TABLES THAT FOLLOW.

							Hard.	Color.	Mineral.
KCN+	HNO_3−	HCl+	$FeCl_3$+	$SnCl_2$+	H_2SO_4+	H_2O_2+	2	Brownish white	Pyrolusite
KCN−	HNO_3+	HCl+	$FeCl_3$+	$SnCl_2$+	H_2SO_4+	H_2O_2+	6	Grayish white	Psilomelane
						H_2O_2−	4	Grayish white	Alabandite
	HNO_3−	HCl−	$FeCl_3$−			H_2O_2 sl.	5	Grayish white	Braunite
							5.5		Franklinite
							5		Manganite
						H_2O_2−	5	Grayish white	Manganosite
							5		Hausmannite
							2		Chalcophanite
				$SnCl_2$−	H_2SO_4−	H_2O_2−	5	Grayish white	Jacobsite
							5		Bixbyite
							6	Grayish white	Columbite
							6		Tantaline
							5.5		Wolframite
							5.5		Hübnerite
				sl.			5–6		Magnetite
				sl.	sl.		5–6	Creamy white	Hematite
							5	Light gray	Limonite

Pyrolusite, MnO_2, Brownish white.

Michrochem.: $SnCl_2$—fumes tarnish brown. Solution becomes dark. Rubs to deeply pitted black surface. H_2O_2 eff. profusely. $H_2O_2 + H_2SO_4$ eff. with etching. $AuCl_3$ plates in 48 hours. Specimens with a hardness of 3 are but partially covered with minute grains of gold on the polished surface.

Hardness: Low, 2–4. Black powder.

Description: Color dark steel-gray to iron-black. Metallic luster.

Diag.: No color reaction with fragments in sulphuric acid. Small portion of finely powdered pyrolusite in test-tube decomposes 2 or 3 cc. of H_2O_2 in a few minutes with marked eff. Manganite requires an hour or more for the same reaction. Pyrolusite decolorizes a drop of 20/N sol. of potassium permanganate on polished surface in 2 or 3 minutes. Manganite requires a much longer period.

Occurrence: Frequently as reniform coatings associated with other manganese minerals. Commonly columnar, also granular massive.

Psilomelane, Light grayish white.

Microchem.: $SnCl_2$ tarnishes with etching; rubs to a gray finely textured etch figure. H_2SO_4 tarnishes brown, rubs to pale brown with slight etching. H_2O_2 eff. profusely; rubs clean. $AuCl_3$, no plating on freshly polished surface, but with electric roast to 950° followed by $AuCl_3$, a film of metallic gold and manganese oxide is deposited.

Hardness: High, 5–6. Black powder.

Description: Black to steel-blue, amorphous, dense, has a concoidal fracture. Submetallic luster; nearly black streak.

Occurrence: Massive or in botryoidal, reniform or stalactitic masses. Widespread in its distribution, and associated with all the other oxides of manganese.

Alabandite, MnS. Grayish white.

Michrochem.: HNO_3 eff. and tarnishes; rubs gray with solution pits. Fumes tarnish brown. HCl same as HNO_3. $SnCl_2$, fumes tarnish; H_2S liberated; slightly etched. H_2SO_4, same as $SnCl_2$. Other reagents negative.

Hardness: Medium, 3.5–4. Sectile, but slightly brittle. Olive green powder when scratched.

Description: Color iron-black; internal reflection by inclined light is green. Has perfect cubic cleavage.

Occurrence: A primary vein mineral with metallic sulphides.

Braunite, $3Mn_2O_3.MnSiO_3$ Light grayish white.

Michrochem.: $SnCl_2$, turns grayish brown; rubs to a very slightly etched surface. H_2O_2 eff. very slowly and that is confined to fractures. $AuCl_3$ Neg. on fresh surface. Neg. on same surface following roast.

Hardness: High, 6–6.5. Brittle.

Description: Color dark brownish black to steel-gray. Streak same. Commonly granular texture with numerous tetragonal crystal outlines.

Diag.:—Distinguished from manganite on polished surface by lack of a permanent tarnish with $H_2O_2 + H_2SO_4$. Gives gel. silica with hot acid.

Occurrence: Associated with primary manganese silicates and carbonates. Also a product of recrystallization in metamorphic rocks. A common constituent in some deposits of secondary oxides.

Franklinite, Light grayish white.

Michrochem.: $SnCl_2$ tarnishes light brown, marked iridescence at margin, rubs clean. Sometimes shows a delicate, reticulate etch figure. H_2SO_4 very slight tarnish. H_2O_2 neg. Often slight eff. along fractures due to alteration to MnO_2. $AuCl_3$ neg. on fresh surface, also negative following roast.

Hardness: High, 5.5–6.5 Brittle, dark brown to black powder.

Description: Color iron-black; often granular.

Diag.: Yields a coating of zinc oxide on charcoal.

Occurrence: Associated with zinc minerals at Franklin Furnace, N. J.

Manganite, $Mn_2O_3.H_2O$. Grayish white.

Michrochem: $SnCl_2$—a few seconds after application the needle-like grains of the mineral are brought out. Extended action produces a dark surface deeply etched with an irregular pattern. H_2SO_4 fumes tarnish slightly. Rubs to a brownish surface. H_2O_2 slight eff. if allowed to act a minute or more. Tarnishes to a darker gray, especially with H_2O_2 plus H_2SO_4. $AuCl_3$ negative.

Hardness: Medium, 4. Dark brown powder.

Description: Radiating needle-like grains or felt-like mats of minute interlocking needles are characteristic.

Diag.: A (1–1) mixture of sat. sol. $SnCl_2$ + dist. H_2O plus a few drops of concentrated HCl rapidly etches manganite but not pyrolusite. With equal amounts of manganite and pyrolusite, the former will not decompose a given volume of H_2O_2 as rapidly as pyrolusite. Does not decolorize a drop of 20/N potassium permanganate on polished surface as rapidly as pyrolusite.

Occurrence: In metalliferous veins as a product of oxidation of manganese carbonates and silicates. As concentrations and replacements in the zone of cementation in sedimentary rocks. Rarely in residual and lateritic deposits.

Manganosite, MnO. Grayish white.

Microchem.: $SnCl_2$ tarnishes bluish gray; rubs to a gray finely etched surface. H_2O_2 + H_2SO_4 eff., feebly with slight etching. $AuCl_3$ neg.

Hardness: High, 5–6. Brittle.

Description: Color, emerald green when fresh; becomes black on exposure. Occurs as minute octahedrons.

Diag.: Identified by its green powder and green internal reflection.

Occurrence: A rare mineral associated with hausmannite in the manganese ores of Sweden.

Hausmannite, Mn_3O_4. Grayish white.

Microchem.: $SnCl_2$ fumes tarnish with iridesence. Surface brown, rubs to a coarse reticulate etch pattern. Many grains have the appearance of lattice

work. Cleavage brought out. H_2O_2 very slight eff. No tarnish. $AuCl_3$ negative on fresh surface. Plated on surface of amorphous material produced by roasting psilomelane.

Hardness: High, 5–5.5. Brittle.

Description: Color, brownish black. Streak chestnut brown. Gives a deep red solution when fragments are placed in con. H_2SO_4.

Diag.: Distinguished from braunite by its etch pattern and cleavage.

Occurrence: Associated with manganese silicates in some primary vein deposits. Generally with braunite in secondary concentrations.

Chalcophanite, Grayish white.

Microchem.: $SnCl_2$ tarnishes grayish brown. Groups of minute, tabular and needle-like crystals become evident, rubs to a dark gray etched figure. H_2O_2 very slight eff. $AuCl_3$ negative before and after roasting.

Hardness: Low, 2.5.

Description: Color, bluish black to iron black. Streak chocolate-brown.

Diag.: The mineral is distinguished from manganite by its change to a golden bronze color when heated.

Occurrence: Associated with hæterolite as a product of alteration of franklinite at Franklin Furnace, N. J.

Jacobsite, Grayish white. Rare.

Michrochem.: Negative to all reagents used.

Hardness: High, 6. Brittle.

Description: Deep black color, brilliant metallic luster; streak blackish brown. Strongly magnetic. With soda yields a manganese bead.

Bixbyite, Light grayish white. Rare.

Microchem.: Negative with all reagents used.

Hardness: High, 6–6.5. Brittle.

Description: Occurs in cubes. Non-magnetic. Gives test for manganese.

Columbite and Tantalite.

Microchem.: Negative with all reagents used. Indistinguishable on polished sections.

Wolframite, Grayish white.

Microchem.: Negative with all reagents.

Hardness: High, 5–5.5. Brittle.

Description: Color, dark brown to nearly black. Streak reddish or brown to nearly black. Perfect pinecoidal cleavage. Crystals commonly tabular, bladed, columnar. Gives test for tungsten.

Hübnerite, Light grayish white.

Same as wolframite, but has a brown internal reflection. Does not give a test for iron.

Magnetite, Grayish white.

Microchem.: $SnCl_2$ tarnishes brown. Negative with all other reagents used.

Hardness: High, Brittle.

Description: Color, iron-black. Streak black. Strongly magnetic.

Hematite, Creamy white.

Microchem.: Negative with all reagents used.

Hardness: High, Brittle. Red to gray powder.

Description: Reddish brown, steel-gray, to iron-black. Streak cherry-red. On charcoal in R. F. becomes magnetic.

Limonite, Light grayish white.

Microchem.: $SnCl_2$ stains to a darker gray. H_2SO_4 slight brownish tarnish, rubs clean. Negative with all other reagents.

Hardness: High, 5–5.5 Brittle, yellow powder.

Description: Color, ocher-yellow to brownish black. Internal reflection is often reddish-brown.

Occurrence: As botryoidal, massive or earthy products of oxidation of iron-bearing minerals.

RELATIONS OF THE OPAQUE MANGANESE MINERAL.

It is too early in the investigation to state whether the following alterations and replacements of the manganese minerals can be regarded as the only ones, or to determine whether they represent all of the essential ones, for much of the material was chosen at random without detailed information concerning the geologic structure of the district supplying them. The textural relationships, however, reveal combinations that can never be solved by chemical analyses alone, and only after the detailed microstructure is thoroughly understood can analyses be interpreted intelligently.

Pyrolusite.—Pyrolusite is one of the commonest manganese minerals in the manganese ores of lateritic origin. It is an abundant constituent in the extensive deposits of the Appalachian region, many of which are residual. In Virginia, where the ores have been extensively exploited, much of the manganese is associated with the basal beds of the Shady dolomite of Cambrian age. Apparently the most favorable conditions for the accumulation of the ores are found in structural synclines floored by quartzite. Direct evidence concerning the origin of the ore is lacking, but from the data available it appears that the manganese was originally widely disseminated as carbonate,[5] and later became segregated into nodules or concretions in the shale, dolo-

[5] Hewett, et al., Virginial Geol. Survey Bull. 17, p. 54.

mite, and limestone which make up the Shady dolomite. At the Crimora mine, in Augusta County, Virginia, much of the ore is pyrolusite pseudomorphic after radiating needles of manganite. (See Analyses, Sample III., Table II.) Polished surfaces of ore specimens from the Crimora mine show many remnants of manganite grains that have not been entirely replaced by pyrolusite. Much of the pyrolusite of the Russian deposits is concretionary and pisolitic. Botryoidal surfaces of pyrolusite enclose hard concentric cores of psilomelane that have not been altered.

In the lateritic deposits of manganese in India, pyrolusite is most commonly present as an alteration product of braunite and psilomelane. The ores are associated with Archean metamorphic rocks, especially with the Dhawar sediments.[6]

Fermor states that the manganese ore and associated rocks were originally laid down as sediments, the manganese probably being in the form of oxides and the associated sediments being clay, marl, and sand of varying coarseness. Metamorphism altered the clays to phyllites and mica-chists, and where beds of pure manganese oxide occurred, the metamorphism resulted in hardening and recrystallization to braunite.

Many specimens of the braunite ore show an alteration of braunite to pyrolusite. Some of the polished surfaces of pyrolusite exhibit marked variations in texture. Due to differences in the hardness of the mineral, such variations are often evident in a single specimen. This is especially true where grains are cut in different directions relative to the crystallographic faces of the mineral grain, for some faces take a much better polish than others.

In the deposits of the Minas Geraes district of Brazil[7] much of the pyrolusite owes its origin to surface-oxidation products of crystalline schists high in manganese-silicate and carbonate minerals. Derby classifies the rocks of the district into two

[6] Fermor, L. L., "The Mineral Deposits of India," Mem. Geol. Survey India, vol. 37, 1910.

[7] Derby, O. A., "Manganese Ore Deposits of Brazil," *Am. Jour. Sci.*, 4th ser., vol. 25, p. 213, 1908.

groups: (1) those occurring in a complex of granite, gneiss, and crystalline schist, and (2) those occurring in overlying metamorphosed sediments. He concludes that the manganese ores associated with the sedimentary rocks consist of mixtures of pyrolusite and psilomelane. From their occurrence he assumes that they are original sedimentary deposits of manganese oxide which have been somewhat altered and recrystallized by metamorphism.

Most of the pyrolusite of the Cuyuna range has been produced by an alteration of manganite. Polished surfaces of pyrolusite pseudomorphous after manganite can be identified most satisfactorily by etching the surface for a few seconds with a dilute solution of stannous chloride and hydrochloric acid. The radiating texture of the needle-like grains of pseudomorphous pyrolusite is conspicuously brought out. Locally, along fractures and contacts, one end of a manganite needle may be altered to pyrolusite, whereas the opposite end of the crystal remains as unaltered manganite.

Some of the pyrolusite of the Blue Ridge deposits of Virginia has the crystalline form and hardness of manganite, but chemically it appears to possess the properties of both minerals.[8] Similar characteristics were observed in Cuyuna range minerals, and a study of polished sections revealed the cause of the variations in the chemical composition of the minerals. Many specimens that appeared to be composed of one mineral species were found to consist of mixtures of pyrolusite, psilomelane, and manganite.

Because some analyses show that manganite has changed most of its chemical properties to coincide more closely with pyrolusite, even though it partially retains the physical properties of manganite, Fermor suggested[9] the term pseudo-manganite for the mineral.

After making a careful study of selected specimens that were polished on four surfaces to determine the amount of alteration,

[8] Stose, G. W., and Schrader, F. G., "Manganese Deposits of East Tennessee," Res. Tenn., 1918–1919, p. 161.

[9] Fermor, L. L., "The Manganese Ore Deposits of India," Mem. Geol. Surv. Indie, vol. 37, 1909.

the writer is of the opinion that many of the determinations that show wide variations in specific gravity, hardness, and water content of manganite, were made of material containing a mixture of manganite and pyrolusite, and possibly psilomelane. Table IV. gives the results of the analyses of mixtures, together with the physical properties and textural relationships of the minerals.

TABLE IV.

ANALYSES OF MIXTURES OF PYROLUSITE, PSILOMELANE, AND MANGANITE.
G. A. Thiel, Analyst.

	I.	II.	III.
Total Mn	59.81	60.82	61.05
Oxygen (calc.)	31.85	30.44	26.61
Comb. H_2O	3.47	7.18	8.27
BaO	1.12	0.00	nd.
CaO	Trace	nd.	2.10
SiO_2	.27	Trace	.92 CO_2
	95.39	98.44	98.95
Sp. G.	4.538	4.772	4.418
H	4.5	3.5	4.0

I. A mixture of pyrolusite and psilomelane. Mineral Ridge mine, Zepp, Va. The specimen contained approximately twice as much psilomelane as pyrolusite. This ratio was used in the calculation of the combined oxygen in the manganese. A small amount of yellowish clay lined the pores of the specimen. Polished surfaces showed concentric layers of psilomelane alternating with thin layers of pyrolusite. Groups of radiating pyrolusite needles filled the spaces between the concentric masses of psilomelane.

II. A mixture of manganite and pyrolusite, Hillcrest Pit, Cuyuna range. Polished surface showed a few microscopic grains of limonite not entirely replaced by manganese. Manganite and pyrolusite in the ratio 2 : 1. Note the low water content as compared with the manganite analyses, Table III.

III. Manganite and psilomelane, Gustavus Claim, Little Grand District, Utah. (See Bull. 725, U. S. G. S., p. 202.) Polished surface shows psilomelane beginning to replace manganite; also remnants of a carbonate gangue. The high water content as shown in this analysis also favors the presence of psilomelane rather than pyrolusite. Microchemical reactions on polished surfaces corroborate the analytical results.

From the numerous specimens of pyrolusite examined, its relation to the other manganese minerals may be summarized as follows:

1. It replaces manganosite, manganite, psilomelane, hausmannite, braunite, rhodonite, and rhodochrosite.

2. It is replaced by braunite and psilomelane.

In some of the deposits it occurs as a primary constituent of sedimentary beds.

Psilomelane.—Psilomelane is concentrated as replacement deposits in many types of rocks and minerals. It tends to be precipitated as concentric and concretionary masses, and does not occur as pseudomorphs with crystal outlines as frequently as pyrolusite. It owes its origin to the alteration of all the other oxides of manganese or to direct precipitation as psilomelane.

In India it is most often associated with braunite; in Brazil and Russia it is common as an alteration product of manganite and pyrolusite. In the North American deposits it is finely disseminated through hausmannite in the Batesville district; it forms boulders in the residual deposits of the Piedmont region of Virginia, and botryoidal and stalactitic masses in the oxidized zones of many of the vein deposits of manganese in the western part of the United States. On the Cuyuna range band-like groups of rods or stalactites of psilomelane extend parallel with the bedding, especially where the beds are steeply inclined. The rods are often coated with brilliant red oxides of iron or locally variegated coloring is produced by various ferrous and manganous salts. Such coloring is conspicuous in the Portsmouth and Hillcrest pits.

Because of the non-crystalline character of psilomelane, no characteristic sections of mineral grains, or outlines of crystal forms can be expected under the microscope. The mineral is easily identified by its hardness and the rapidity with which a drop of hydrogen peroxide is decomposed when placed on a polished surface. No other manganese mineral with a hardness of psilomelane shows a similar reaction.

Where psilomelane occurs as fine grains in an intimate mixture with hausmannite or braunite, or as an alteration product of manganite or pyrolusite, no diagnostic texture is evident. However, where larger quantities have been formed by replacement, the concentric structure is conspicuous. Often alternating lay-

ers have a varying hardness. This is clearly demonstrated by variations in the degree of polish on a section of a small nodule or stalactitic mass. There are several varieties of psilomelane with varying water content and one may assume that the softer layers represent the more hydrous varieties. Two generations of psilomelane are frequently encountered in a single nodule. Numerous concretionary nodules from the Sagamore, Hillcrest, Portsmouth, and Mahnomen pits on the Cuyuna range show irregular or radial contraction cracks filled with a later generation of the same mineral. Similar relations are reported in ores from Virginia, where the structure of some resembles that of septaria in which the cracks are filled with psilomelane of a greater hardness. The cracks are said to be small and numerous, and are confined to the softer psilomelane, but some flattish nodules are split by a single crack which has been healed by successive layers of psilomelane that are continuous with the external layers.[10] Often the fractures are filled with brilliant needles of manganite which gives the ores a brecciated appearance.

Many specimens of Batesville ore, examined on polished surface, show psilomelane replacing hausmannite and the psilomelane in turn being replaced by braunite. In the latter case the process may simply be recrystallization with the addition of silica. Psilomelane alters to wad; the reverse reaction is also suggested.[11]

The prevalent nodular character of psilomelane has often been emphasized, but nothing definite or conclusive has been suggested as to the origin of the form. This form is not confined to psilomelane, for variations in the composition of the solutions that were instrumental in the development of the nodules oftimes produce concentric layers of psilomelane alternating with other minerals. Among those observed by the writer are: manganite, pyrolusite, hausmannite, hæterolite, chalcophanite, limonite, quartz, calcite, siderite, and barite.

[10] Stose, G. W., Miser, H. D., Katz, F. J., and Hewett, D. F., "Manganese Deposits of the West Foothills of the Blue Ridge, Virginia," Va. Geol. Survey Bull. 17, 1917.

[11] Stose, G. W., and Shrader, F. C., Min. Res. Tenn., 1918–19, p. 153.

A summary of the observations on polished specimens of psilomelane indicates that it replaces or is produced by an alteration of pyrolusite, manganite, hausmannite, braunite, rhodonite, and manganiferous carbonates. It is sometimes replaced by pyrolusite and braunite.

Braunite.—Braunite may be formed in three different ways.

1. By crystallization from an igneous intrusive.
2. By the metamorphism of manganiferous sediments.
3. By the alteration of manganese silicates, such as manganese garnets and pyroxenes.

Braunite is associated with rhodonite and rhodochrosite, in the few cases where it occurs as a primary constituent of igneous intrusives. In the Nágpur district of India braunite crystals are found in abundance in an albite rock that is intrusive into a manganese ore body.[12] In the Philipsburg district and in various smaller deposits in Nevada and California it is associated with primary silicates, but most if not all of the braunite is secondary.

Braunite generally appears granular (see Plate I., B), on polished surface because of its strong tendency to form small octahedron-like crystals. This crystalline character is so pronounced that contacts of braunite with carbonate or silicate gangue minerals that are being replaced, show sharp angular "saw-tooth" textures where the tetragonal grains penetrate and replace the gangue. Pardee has reported braunite with rhombohedral cleavage. It is possible that such a structure is pseudomorphic after a carbonate, but euhedral tetragonal crystals are most commonly developed where braunite replaces calcite. The same texture is evident when braunite replaces quartz, barite, and rhodonite, or when braunite is formed by the recrystallization of hausmannite, psilomelane, and pyrolusite.

Specimens of braunite ore from the Harz Mountains, from Langban, Sweden; and numerous specimens from the Batesville district show it as an alteration product of psilomelane and haus-

[12] Fermor, L. L., "The Manganese Ore Deposits of India," Mem. Geol. Surv. India, vol. 37, 1909.

mannite. In the ore from each of these regions, many grains show inclusions of psilomelane that were not replaced as the mineral recrystallized. The order of deposition where the three minerals are associated is hausmannite, psilomelane, braunite, with a second generation of psilomelane as an alteration of the braunite along fractures and contacts of mineral grains. Psilomelane and braunite are also found where rhodonite and rhodochrosite have been subjected to oxidation, but psilomelane is not always present as an intermediate product.

The numerous specimens from widely separated districts indicate that secondary braunite replaces, or is formed by the recrystallization of pyrolusite, psilomelane, hausmannite, rhodonite, and rhodochrosite.

Manganite.—In most of the producing districts, manganite is found in relatively small amounts, due to the ease with which it alters to pyrolusite or psilomelane. Its presence, however, seems to indicate precipitation at considerable depth.

Nearly every specimen of Cuyuna range manganese ore contains some manganite. It is generally present as groups of radiating needles or fibers that line druses and cavities and it is conspicuously developed along fractures in the nodules of psilomelane. In some of the mines concentric layers of manganite have built up nodules a foot or more in diameter similar to the psilomelane nodules that are characteristic of lateritic deposits.

Nodular manganite ore is composed of concentric layers of needle-like crystals of the mineral. The layers vary in thickness from less than a millimeter to several centimeters. Each layer has its own peculiar arrangement of crystals; three different types are common. (1) Layers of varying thickness with individual needles extending across the entire width of the layer. (2) Needles about one half centimeter in length, with their axes parallel and dove-tailed to build up a layer an inch or more in thickness. (3) Short delicate fibers in an irregular arrangement, forming a felt-like layer. The latter type is generally present as very thin lamellæ between the other two.

Another form of manganite grains is found in quartz veins

at the Mahnomen pit on the Cuyuna range. The mineral is in groups or bundles of short crystals with vertically striated prism faces. The manganese is confined to fractures and cavities in the quartz. In the larger cavities, are groups of interlocking short prisms that appear to be cut by numerous macrodomes. On polished surface the secondary nature of the manganese becomes more evident. In many of the groups of crystals, manganite is replacing quartz, and numerous small concentric masses of psilomelane are surrounded by radiating needles of manganite. In a few cases the inner core is composed of a dense mass of fine manganite needles around which the psilomelane is arranged in concentric layers.

The physical and chemical properties of sample V. in Table II. B are of special interest in view of the fact that the mineral showed an unusual crystal form for manganite. Its physical properties, chemical constituents, and microchemical reactions coincide with those of manganite of other regions. The small amount of SiO_2 indicated in the analysis was undoubtedly derived from the gangue of the vein, as the manganite was in groups of crystals in massive vein quartz. The crystal outlines of the manganite, however, appear similar to those described by Watson and Wherry[13] for the pyrolusite crystals from Shenandoah County, Virginia. Because of the unusual axial ratio of the pyrolusite crystals (an abnormal habit for manganite), it was suggested that the pyrolusite might be original; that is, it may have a distinct crystal form of its own, and not be pseudomorphic after manganite. The structure and composition of the manganite crystals at the Cuyuna pit show, however, that manganite may crystallize as very similar wedge-shaped crystals. Since most of the pyrolusite of the Cuyuna Range is pseudomorphic after manganite, and especially since some of the wedge-shaped grains of manganite show evidence of alteration to pyrolusite, it seems possible that the Virginia pyrolusite may also be pseudomorphic.

[13] Watson, T. L., and Wherry, E. T., "Pyrolusite from Virginia," *Jour. Wash. Acad. Sci.*, vol. 8, p. 550, 1918.

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Hausmannite.—In determining the paragenesis of hausmannite, numerous specimens of ore from Langban, Sweden; Ilmenau and Œhrenstock, Thuringen; Batesville, Arkansas; and from the deposits near Bromide, Oklahoma, were studied. An intimate association of hausmannite with braunite is noted in the ores from Langban and Ilmenau; coarsely crystalline hausmannite that exhibits definite cleavage lines after a treatment with $H_2O_2 + H_2SO_4$, shows numerous euhedral crystals of braunite in the larger mineral grains. Where both minerals are finely granular, braunite shows the greater tendency to develop definite crystal outlines. Even grains a small fraction of a millimeter in diameter exhibit tetragonal crystal characters. Many of the hausmannite grains are partially replaced by braunite. This alteration is most commonly seen along the margins of crystals of hausmannite. Some grains of braunite show corroded cores of partially altered hausmannite and psilomelane.

In the Batesville district the hausmannite occurs associated with psilomelane and braunite. According to Miser,[14] the oxides have been derived from manganese-bearing carbonates near the surface and have been deposited by cold waters of meteoric origin. They do not extend below the permanent water level of the district. The workable deposits occur in the nearly horizontal Fernvale limestone and Cason shale and in residual clays derived from these two formations. Much of the hausmannite occurs in the replacements of the Fernvale limestone; none of it is in the replacement deposits of the Cason shale. Miser, therefore, concludes that there was a smaller supply of available oxygen for the formation of manganese oxides in the limestone than in the shale and clays, because hausmannite contains a smaller percentage of oxygen than the other manganese oxides of the district.

Specimens of ore from the Batesville district show the presence of several manganese oxides, but nearly all of the hausmannite occurs in an intimate mixture disseminated through compact psilomelane. Some specimens show a gradation from psilomelane with a few grains of hausmannite scattered through it, to a

[14] *Op. cit.*

coarse granulated hausmannite with only a small quantity of psilomelane. Several samples from this district have braunite associated with the hausmannite. Such an association is common in European deposits, but has not been noted heretofore in North America.

At Bromide, Oklahoma, hausmannite is also associated with carbonate minerals. The commonest mineral, as determined by Jewett,[15] is a carbonate of manganese, calcium and magnesium, that occurs as irregular fine-grained masses. The hausmannite is intimately intergrown with the carbonate as delicate plumose masses, and the two minerals appear to have been the first that were deposited. Hausmannite occurs as minute octahedral crystals on the borders of the manganiferous carbonate, and some is found in the same form lining druses and cavities.

Near San Jose, California, hausmannite occurs in a large boulder weighing several hundred tons that is of Franciscan age.[16] Here the mineral is associated with tephroite, pyrochroite, ganophyllite, rhodochrosite, barite, and psilomelane. In some of the mass hausmannite is the most abundant mineral present and appears to have been formed later than the tephroite, for vein-like areas of hausmannite surround and extend into areas of tephroite and there is no evidence of more than one generation of the hausmannite.

Although most of the specimens of all of the districts show psilomelane later than hausmannite, yet some ores indicate that the two minerals were deposited simultaneously. This is especially true of the carbonate ore from Bromide, Oklahoma, where narrow concentric layers of the minerals alternate in plumose masses.

The relation of hausmannite to the common minerals of manganese, as seen in the specimens examined, may therefore be summarized briefly as follows:

1. It replaces manganiferous carbonates and manganosite.
2. It is replaced by psilomelane, braunite, and pyrolusite.

[15] *Op. cit.*

[16] Rogers, A. F., "Occurrence of Manganese Minerals near San Jose, California," *Am. Jour. Sci.*, vol. 48, p. 443, 1919.

3. It shows intergrowths with psilomelane that indicate contemporaneous deposition.

Rhodonite.—Rhodonite, the pink silicate of manganese, is not an opaque mineral, but because of its relation to a series of oxides of manganese, its alteration is briefly outlined. It occurs as a gangue in veins of metallic ores and is sparingly present in pegmatite veins. It is found as a product of contact metamorphism as fowlerite, in the ores of Franklin Furnace, New Jersey. Its presence in schistose rocks both in North America and in India also implies its formation through recrystallization under the agents of dynamic metamorphism.

Pure rhodonite contains about 42 per cent. manganese. There is a strong possibility, however, that when other constituents are present in the sediments the manganese forms silicates that contain a smaller percentage of manganese, such as manganiferous pyroxenes and manganese garnets.

In the deposits of India, numerous spessartite-rhodonite-braunite rocks are encountered which Fermor [17] considers as products of metamorphism of pre-Cambrian sediments.

A study of thin sections and polished surfaces of rhodonite from various districts in the United States affords abundant evidence that a variety of oxides are formed as alteration products of the mineral. Where the rhodonite alters to braunite, psilomelane may be produced as an intermediate product. The psilomelane contains minute grains of an oxide that are too small for exact determination, but the microchemical reactions suggest iron oxides. A soft brownish mineral may separate the braunite from the unaltered rhodonite. The material gives a manganese reaction, but it is lighter in color than any pure manganese oxide. Often rhodonite is replaced directly by braunite, which may occur by the addition of manganese in solution.

In some cases the alteration product is psilomelane and a soft earthy oxide that is undoubtedly wad. A few specimens show secondary manganite, but its relation to the rhodonite indicates

[17] Fermor, L., "The Manganese Ore Deposits of India," Mem. Geol. Survey India, vol. 37, 1909, p. 290.

an addition of manganese rather than direct alteration, as the manganite was confined to fractures and cavities in the unaltered rhodonite. The order of alteration, therefore, appears to be (1) The formation of an intimate mixture of oxides of manganese and iron; (2) The replacement of this mixture by psilomelane; (3) Recrystallization of psilomelane into braunite. The last stage of recrystallization is not always reached.

Rare Manganese Minerals.—Manganosite (MnO) occurs as minute octahedrons that show cubic cleavage. It has an emerald-green color when fresh and on polished surface shows a green streak and a green internal reflection.

Pyrochroite ($MnO.H_2O$) is sometimes associated with hausmannite in the deposits of Sweden.[18] It has also been identified at Franklin Furnace, New Jersey,[19] where it occurs in pearly, colorless, foliated masses like brucite.

Prophanite ($MnTiO_3$) may be regarded as isomorphous with ilmenite ($FeTiO_3$). It is found sparingly in Wermland, Sweden, associated with granophyllite, manganophyllite, and garnet. It has also been reported from the Piquiry deposits of manganese in Brazil. It occurs in thin scale-like flakes that are brilliant red in color.

Dysluite $(ZnFeMn)O.(AlFe)_2O_3$ is a zinc-manganese-spinel, and crystallizes as octahedrons. It is yellowish-brown to grayish brown in color and has a specific gravity of 4–4.6, and a hardness of nearly 8. It is a vein-forming mineral and is generally associated with biotite and feldspar.

Franklinite $(FeZnMn)O.(FeMn)_2O_3$, also a manganiferous spinel, occurs associated chiefly with zinctite and willemite at Franklin Furnace. Here these minerals constitute most of the ore, but elsewhere they are extremely rare. Their order of paragenesis has been studied in detail[20] and characteristic secondary minerals such as chalcophanite and hæterolite, have been distinguished.

[18] Flink, J., Nordmark. Ak. Hand., Stockholm, vol. 12, 1886.

[19] Palache, Chas., U. S. Geol. Survey Folio 161, 1908.

[20] Ries, H., and Bowen, W. C., "Origin of the Zinc Ores of Sussex County, N. J.," ECON. GEOL., vol. XVII., p. 517, 1922.

Summary.—1. The following table shows possible relations between the various manganese minerals. Manganiferous silicates other than rhodonite are not included. The minerals in the columns have been found altering to or replaced by the mineral at the top of the column.

Derived product.→	pyrolusite	psilomelane	braunite	manganite	hausmannite
	↑	↑	↑	↑	↑
	manganosite	pyrolusite	pyrolusite		manganosite
	manganite	manganite			
Original minerals from which it is derived	psilomelane		psilomelane	psilomelane	rhodochrosite
	hausmannite	hausmannite	hausmannite		
	braunite	braunite			
	rhodonite	rhodonite	rhodonite	rhodonite	
	rhodochrosite	rhodochrosite	rhodochrosite	rhodochrosite	

2. The opaque manganese minerals as a group show no uniform order of deposition. There is no systematic change from manganous to manganic forms, nor is there a definite order from the more hydrous to the less hydrous, or vice versa. The common replacement of other minerals by pyrolusite, however, suggests a tendency toward progressively higher oxidation and in many cases dehydration following the initial precipitation.

3. Manganite and pyrolusite are intimately associated. Numerous specimens show manganite crystals that are partially altered to pyrolusite. The manganite very commonly is the first to crystallize where veins of primary manganese minerals are oxidized by percolating ground waters. Near the surface, however, pyrolusite develops direct pseudomorphs after carbonates and silicates.

4. Of all the opaque manganese minerals braunite shows the greatest tendency to develop euhedral mineral grains, thus producing a granular texture that is characteristic on polished surfaces, especially if slightly etched. It is a common product of psilomelane and hausmannite produced by the addition of silica,

and it frequently replaces rhodochrosite, calcite, barite, and quartz.

5. Variations in the hardness of psilomelane are found in different concentric layers of nodular ore. Some concretionary ore shows other minerals alternating with the layers of psilomelane. Those observed are: manganite, pyrolusite, hausmannite, hæterolite, chalcophanite, limonite, quartz, calcite, siderite, and barite. Psilomelane alters to wad. It was also found replacing hausmannite, rhodonite, rhodochrosite, braunite, and manganite. It may by hydration recrystallize to form manganite, which is in turn altered to pyrolusite by dehydration.

6. Hausmannite replaces manganosite and rhodochrosite. It alters to psilomelane which is in turn replaced by braunite with the addition of silica. No replacement or alterations of hausmannite to manganite were evident in the ores examined.

7. Manganosite (MnO), the protoxide, generally occurs with the hydroxide, pyrochroite. Both are rare minerals, and in all specimens examined, hausmannite is a later mineral than manganosite and sometimes replaces it. This alteration indicates oxidation, as hausmannite has the formula Mn_3O_4.

RELATIONS OF MANGANESE AND IRON MINERALS IN MANGANIFEROUS IRON ORES, WITH SPECIAL REFERENCE TO THE CUYUNA RANGE.

Introduction.—A resume of the manganese deposits of the world indicates that many of the manganese oxides are associated with iron minerals forming manganiferous iron ores. Of the group of manganese oxides, manganite, psilomelane, and pyrolusite are most commonly associated with the iron oxides. On the Cuyuna Range manganite is by far the most abundant manganese mineral. Pyrolusite and psilomelane are also present, but in most cases they represent an alteration of the manganite that replaced the cherty carbonate slates.

Study of thin sections and polished surfaces indicates that manganite was the first manganese oxide in the series of man-

ganese replacements, and was undoubtedly deposited at considerable depth (Plate IV., *B*). It replaces quartz, manganiferous calcite, siderite, rhodochrosite, fibrous amphiboles, epidote, green hornblende, biotite, and both hematite and limonite.

General Geology.—The principal constituents of the pre-Cambrian metamorphic rocks are irregularly interbedded chloritic, micaceous, quartzose, and hematite schists.[21] Associated with the schists are numerous beds of cherty carbonate and locally lenses of quartzite and slate. The cherts are ferruginous and either massive or banded. The beds high in carbonate are usually green in color, fine-grained and somewhat argillaceous. Locally they become schistose, and grade into slaty carbonate rocks. The slates are banded rocks high in carbonate.

The following lithologic succession was suggested by Mr. Frank Kray[22] and has been modified by the writer to include features exposed by more recent developments:

5. Basic intrusives.
4. Dark, massive ferruginous chert.
3. Gray-green carbonate rock.
2. Thin-bedded pink chert.
1. Calcareous quartzite beds.

At the Moroco pit the unaltered rock is a thin-bedded pink chert. Southward toward the Hopkins mine the pink chert grades into a green carbonate rock. Some beds of the carbonate are massive and soft with no distinct minerals, others are cherty and schistose, and still others are slaty and finely laminated. Magnetite and radiating groups of green and brown amphiboles are abundant in some layers. Analyses show that such varieties may contain when fresh, as much as 45 per cent. iron and 6 per cent. manganese. The thickness of the green formation is between one and two hundred feet.

Further south the Sultana ore body appears to be at the same horizon as the rock at the top of the Hopkins shaft. Here the

[21] Harder, E. C., and Johnston, A. W., "The Geology of East-central Minnesota," Minn. Geol. Survey Bull. 15.

[22] Unpublished notes, University of Minnesota.

carbonate beds have graded into dense black chert which alters to a red hematite slate and fine-grained, brown, quartzose schist. Locally, beds higher in carbonate alter to reddish-yellow ocherous ore which contains nodules of manganese. The dark cherty horizon that is typically demonstrated at the Sultana mine is also represented at the Mahnomen and Pennington pits and at the latter it is intruded by a basic intrusive that forms the grayish-green chlorite and sericite schist of the south wall of the Pennington pit. Further south, at the Bonnie Bell mine, the basic rock is not as intensely metamorphosed and thin sections reveal the igneous texture of the rock. It therefore appears as if the iron ores of the southern portion of the range that are low in manganese, are stratigraphically higher than the manganese mines of the carbonate horizon extending from Mahnomen Lake southwestward to the Sagamore pit and northeastward to the Northland mine. Fig. 11 shows a generalized cross-section from the Pennington to the Moroco pit.

The correlation of the Deerwood iron formation with the iron-bearing members of the other Lake Superior districts is still an open question, but more data are being collected which point to a close relationship between it and the Biwabik formation of the Mesabi Range. Thin sections of ferruginous chert from the Deerwood formation show altered greenalite grains. Specimens of algal structures similar to the algæ found in the algal horizons of the Mesabi Range have been collected by Dr. Gruner and the writer in several of the pits on the Cuyuna. At the Moroco pit algal structures were found immediately to the south of quartzite. These are tentatively correlated with the Pokegama quartzite and overlying algal beds of the Mesabi Range.

The cherty iron carbonate of the Cuyuna district differs somewhat from the typical cherty rock of the other districts. On the Mesabi Range the ferruginous chert is mostly of the type known as taconite, an irregularly bedded cherty rock speckled with iron oxide. On the Cuyuna Range the varieties are equally numerous. Thin sections show most of them to contain varying amounts of chert, siderite, rhodochrosite, calcite, and fibrous or needle-like

amphiboles. The slates rarely show slaty cleavage, but are rather indurated ferruginous argillites. In all the classes of rocks both iron and manganese are persistent constituents.

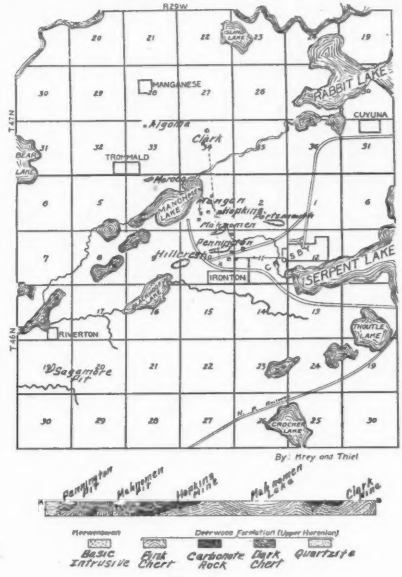


FIG. 11.

By comparing analyses of the carbonate rocks with those of the cherty phases, it is at once evident that the former are higher in manganese. Twelve analyses of different ferruginous cherts of the Cuyuna Range, analyzed at the Minnesota School of Mines Experiment Station, show less than 1 per cent. manganese, whereas a similar number high in carbonate show from 2 to 6 per cent. manganese. The lithologic succession as interpreted by the writer (Fig. 11) places the carbonate rocks in a horizon lower than the dark ferruginous cherts, and field observations indicate that all of the mines that have produced high-grade manganese ore are located in this horizon. The same is true to a limited extent in the iron mines, for in them also partially or

entirely replaced carbonate beds carry the highest percentage of manganese. Where there is an erratic distribution of manganese along the strike it can often be explained by zones of intense fracturing and slumping crossing the strike of the beds.

High Phosphorus, Low Silica Ores.[23] The high phosphorus ores are most commonly found in zones with abundant soft pyrolusite and smaller amounts of nodular psilomelane, associated with ocherous limonitic material, whereas, the low phosphorus varieties contain mostly hard crystalline, manganite and numerous nodules of massive, dark blue, dense psilomelane.

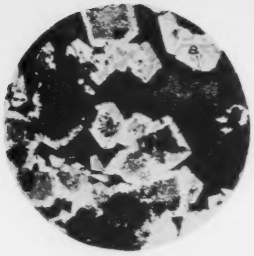
The predominance of limonite instead of hematite associated with the soft pyrolusite ores suggest a direct replacement by limonite of gray-green slates rather than ferruginous chert. For, as has been pointed out on the Mesabi Range,[24] limonite is more commonly derived from ferromagnesian minerals, iron carbonate, and greenalite, than from magnetite and hematite. Much of the manganese is present as thin lamellæ less than a quarter of an inch in thickness alternating with bands or beds of limonite. Sometimes stringers of pyrolusite cut from one sheet to the other, with a replacement of limonite along the margins of minute fractures. Thin sections of altered phases of the same horizons show limonite replacing the gangue minerals and it in turn replaced by manganite.

Low Phosphorus High Silica Ore.[25]—The high percentage of silica in the so-called low phosphorus ore indicates incomplete replacement of ferruginous chert rather than slate, as the cherty rocks contain a much higher percentage of SiO_2. This, together with the more common association of hematite with manganese, lends support to such an interpretation, for hematite is more frequently found than limonite as an alteration product of jaspery ferruginous chert. The manganese is largely in the form of manganite and nodular psilomelane. In the hematite chert, most

[23] For analyses see Newton, E., "Manganiferous Iron Ores of the Cuyuna District, Minn.," Minn. Sch. Min. Exp. St. Bull. No. 5, p. 15, 1918.

[24] Gruner, J. W., "Paragenesis of the Martite Ore Bodies and Magnetites of the Mesabi Range," ECON. GEOL., vol. 17, p. 1, 1922.

[25] Newton, *loc. cit.*



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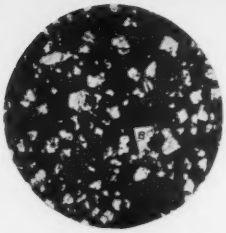

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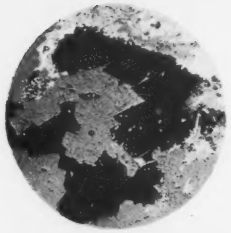

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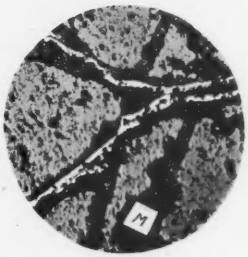

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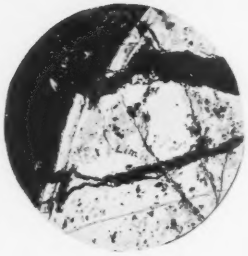


F

A. Euhedral grains of braunite (*B*) in psilomelane (etched black). Batesville, Ark. × 40.

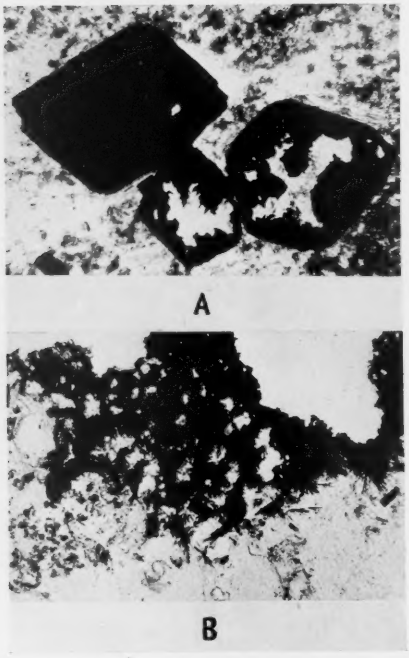
B. Intimate mixture of braunite (*B*) and psilomelane (black), etched with stannous chloride to distinguish the two minerals in massive ore. Harz Mts. × 40.

C. Pyrolusite (*P*) replacing manganite (etched black) in a quartz (*Q*) gangue. Differential etching produced by dilute stannous chloride and hydrochloric acid solution. Sweethome Claim, Philipsburg, Mont. × 40.

D. Etch figure of hausmannite (*H*) developed by stannous chloride. Rounded light grains are manganosite (*M*), dark irregular lines are fractures in hausmannite. Langban, Sweden. × 40.

E. Quartz vein (*Q*) crossed by a specularite (white) vein. Both minerals later replaced by manganite (*M*) along contacts. Portsmouth Mine, Cuyuna Range. × 40.

F. Manganite (etched black) replacing limonite (Lim). Portion of rim of a "stalactite" of limonite, showing replacement along fractures. Hillcrest Mine, Cuyuna Range. × 40.



A. Martite grains with inclusions of quartz and carbonates. The inclusions are sometimes replaced by manganese oxides, thus producing a manganiferous ore. Mangan Mine, Cuyuna Range. × 55.

B. Selective replacement. Manganite replacing a quartz-carbonate rock. The carbonate is replaced first, leaving only inclusions of quartz in the manganite. Note the minute tufts of needles of manganite penetrating the rock. Mangan Mine, Cuyuna Range. × 55.

if not all of the manganese is secondary; manganite and psilomelane are found replacing both hematite and quartz.

As has been stated above, manganite replaces both limonite and hematite, but the replacement of magnetite by any oxide of manganese has not been observed in any of the Cuyuna ores. In the magnetite slates of the south range and to a more limited extent on the north range, magnetite is present as a product of recrystallization of the primary iron minerals (Plate IV., *A*). The alteration of magnetite to martite is frequently encountered and the hematite of the latter is subsequently replaced by manganite.

High-Grade Iron Ores.—The secondary introduction of most of the manganese into the iron ores of the iron belt of the north range is shown not only by the low manganese content of the unaltered rock, but also by the abundance of manganese along the solution channels that cut the ore bodies. Manganite is especially conspicuous in the shattered quartz veins across the strike of the iron formation, and much of it is present in fractures and cavities within the ore bodies. At the Hillcrest and Thompson pits it replaces earlier concentrations of iron that had been deposited as stalactitic and concretionary limonite.

From the field relations as shown in Fig. 11, it is logical to assume that most of the manganese in the high-grade iron ores, was derived from solutions produced by the leaching of the horizons to the north that are higher in both manganese and other carbonate minerals. This does not necessarily imply that all of the manganese was introduced by solutions for even in the horizons of dark ferruginous cherts, thin bands of gray carbonate rocks that may have contained primary manganese are locally interbedded with the chert.

High-Grade Manganese Ore.—The unaltered rocks in the zone of so-called high-grade manganese ore—that is, ore mined for its manganese content—are principally gray-green carbonate slates. Most of the manganese concentrated in this zone owes its origin to highly manganiferous carbonates. Much of the ore has been enriched by the leaching of gangue minerals and the later addition of manganese. Field relations also indicate that the initial

replacements were formed in the zone of cementation below the water table, rather than in the zone of leaching. The predominance of manganite serves as confirmatory evidence in this respect. In the manganese deposits the world over those formed in the zone of leaching are composed for the most part of psilomelane and pyrolusite—or in other words, the oxides with the highest percentage of combined oxygen—whereas, the hydrous oxide, manganite, is more commonly found at greater depth.

The increase in the ratio of manganese to iron in the unaltered and partially altered rocks of the carbonate horizons also suggests that enrichment took place below the zone of extensive leaching, for iron was not added as abundantly as manganese in the enriched zones of manganese ore. If the deposits were in the leached zone, the ratio would be reversed, for under surface conditions manganese is generally more readily extracted from rock than iron.[26] However, data on the relative stability of iron and manganese under various conditions of weathering are still too meager to permit a conclusive statement regarding their vertical distribution.

The form in which manganese is transported in solution is modified by local conditions, but experimental evidence indicates that it may be carried as a sulphate, chloride, bicarbonate, or by organic acids. Subsequent deposition is accomplished by the neutralization of the manganous solutions and accompanying precipitation of manganese oxides.

Hot waters may have played a part in the distribution of manganese in the high carbonate horizon, for narrow dikes containing rhodochrosite cut the slaty sediments. Numerous quartz-rhodochrosite, quartz-siderite, and quartz-specularite veins also cross the slates. The relation of manganite to the veins indicates that the intrusion took place prior to the enrichment of the manganese ore, but later than the period of most extensive metamorphism.

Several quartz veins with abundant specular hematite and

[26] Emmons, W. H., "Manganese and Gold Enrichment," *Trans. Am. Hist. Min. Eng.*, vol. 42, p. 39, 1911.

manganite cut the ore bodies at right angles to the bedding. The presence of specularite in the veins indicates hydrothermal action with accompanying iron solutions. These solutions may have been instrumental in producing the sharp breaks from manganese to high-grade iron ore that are found along the strike of the formation. The manganite is clearly a later mineral as polished sections of the vein material show both quartz and hematite replaced by euhedral crystals of manganite (Plate III., *E*).

CHARACTERISTIC TEXTURAL RELATIONS.

Samples of various phases on the Cuyuna Range manganiferous ores were studied on polished surface and a variety of texural relations were observed. The following association were found in numerous ore bodies: (*a*) manganiferous martite; (*b*) contemporaneous intergrowths of iron and manganese minerals; (*c*) laminated pyrolusite and limonite; (*d*) psilomelane concretions in limonite; (*e*) replacements in carbonate slates; (*f*) porous manganite ore with a low iron content.

Manganiferous Martite.—At the Mangan mine martite, manganite, and pyrolusite are in intimate association. The manganese in the martite ore fills the spaces between the martite grains or where the iron has but partially removed the cherty carbonate bands of the rock, manganese lines the contacts between chert and iron. In a few specimens it was seen as a core in the pseudomorph of hematite. In some of the disseminated euhedral martite grains are minute manganese grains of uncertain origin that can be identified on polished surfaces (Plate IV., *A*).

Contemporaneous Intergrowths.—Ores from the Cuyuna Mille Lac mine show intimate mixtures of hematite, limonite, manganite, and psilomelane that indicate the contemporaneous deposition of some of the oxides. Numerous samples of fairly hard and compact yellowish-brown ore contain minute crystals of manganite. The relation of manganite needles to limonite and hematite, as seen in polished surface, indicates that the limonite and manganite were deposited simultaneously. Of the iron oxides, limonite appears to have been deposited earlier than hematite, for hematite is seen

replacing needles of limonite that are replacements of manganiferous calcite, siderite, ankerite, and groups of fibrous amphiboles.

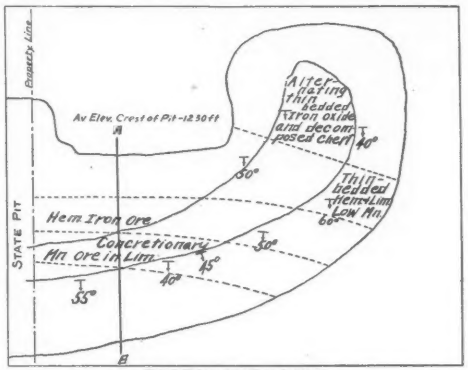
In the same mine is another type of manganiferous iron ore that shows contemporaneous deposition of iron and manganese. Alternating with the beds of hematite that contain the manganite, are thin layers of soft and friable limonite ore in which numerous dense, black psilomelane nodules from one to six or eight inches in diameter are encountered. These seemingly pure manganese oxide nodules show uniform concentric layers of growth in which alternating layers are composed of hematite or limonite. The layers of iron are much narrower than those of manganese, but they become conspicuous under the microscope when the neighboring layers of psilomelane are etched with stannous chloride. Manganese was the last mineral to be concentrated.

Laminated Pyrolusite and Limonite.—Numerous samples collected from the Sagamore mine show alternating thin seams of pyrolusite and limonite ore. Polished surfaces and thin sections of a series of samples selected for a study of the gradation from slightly altered slate to ore, show that the original sediment was a finely laminated deposit in which thin layers of carbonates were interbedded with a fine clayey silt with needles of amphiboles and fine grains of biotite, together with minute grains of quartz. Samples from the same horizon taken near the ore body indicate that the carbonate seams were replaced by manganite, whereas the slaty laminæ were altered to limonitic clay. The pyrolusite was later produced by an alteration of the manganite, thereby leaving a soft pyrolusite ore interbedded with plastic, yellow, pink, blue or variegated ochre.

Along the fractures, manganese has replaced irregular areas in the limonitic ore and various stages in the formation of nodular manganese ore may be observed. In the first stage, stringers of dense black amorphous manganese, mostly psilomelane, are seen cutting a bed of limonite. In others, most of the iron of the bed is removed; that which remains is present in irregular pockets throughout the nodule. A later final stage shows compact bluish manganese ore with a metallic luster, cut by minute

fractures that are filled by a later mineral which in some cases is crystalline manganite, in others psilomelane.

Geodal Psilomelane Concretions in Limonite.—Large boulders or concretions of psilomelane with geodal cavities are conspicuously developed at the Portsmouth mine. This mine is an open pit which is an eastward extension of the State pit (Fig. 12) and



PORTSMOUTH MINE
SE¼-SE¼ Sec 2-T46N-R29W

FIG. 12.

the ore body is a continuation of the iron formation. Striking across the pit from the northwest corner toward the center of the south wall, is a bed of high-grade iron ore low in manganese, composed for the most part of red hematite ore. Further eastward it is followed by a band of yellow, soft, ore low in silica and consistently high in manganese. The hanging-wall has been exposed in the southeast corner of the pit and consists of a pink cherty carbonate rock interbedded with thin bands of white, partially decomposed chert.

A study of selected specimens from the Portsmouth pit shows that the chief manganese minerals are psilomelane and manganite together with some pyrolusite and soft earthy wad. The manganese is present in the clayey limonitic ore of the southwest wall of the pit and can be traced along the strike of the formation.

The hematite ore horizon is relatively free of manganese, excepting where extensive fractures connect it with the manganiferous beds to the north.

The psilomelane occurs as massive boulders and irregular replacements in the soft ocherous ore, many of which contain geodal cavities lined with manganite crystals. Numerous geodes are found in ore that appears to have had a concretionary development, but they occur more frequently in ore which shows a slightly brecciated structure.

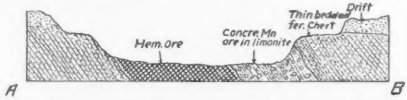


FIG. 13. Cross-section of the Portsmouth Mine, on line A–B in Fig. 12.

Ghase [27] observed similar structures in the ores of India where compact psilomelane shows crystals of manganite lining geodal cavities. Such crystals possess an extremely brilliant luster almost approaching iridescence. On the other hand, in the absence of a strongly coherent envelope of psilomelane, subsequent infiltration has coated the crystals with ferruginous or siliceous incrustations.

Replacements in Green Carbonate Rock.—Samples of partially altered gray-green carbonate rock were collected at Mangan No. 1 mine. The unaltered rocks are mainly slaty green carbonate and pink chert, the former containing 46 per cent. iron and 6 per cent. manganese. The ore occurs as irregular masses in a shallow trough adjoining the Hopkins mine. Manganite and pyrolusite are the most abundant manganese minerals. Much of the ore is composed of massive blocks of manganite in which the original bedding of the sediment is retained.

Thin sections of the slaty green carbonate rock show minute tufts of manganite needles penetrating and replacing the carbonate along the contact with quartz grains and along cleavage

[27] Ghase, A., "The Mode of Occurrence of Manganite in the Manganese Ore Deposits of the Sancher State, India," *Trans. Inst. Min. Eng.* (Great Britain), vol. 35, 1908, p. 685.

cracks of the carbonate. Selective replacement is conspicuously shown. In many of the opaque masses of manganese, the small quartz grains still remain, whereas, the carbonate is entirely removed (Plate IV., *B*). The manganite is later recrystallized into macroscopic groups of radiating needles.

Lumps of lean ore contain masses of crystalline limestone and siderite that gives a positive test for manganese. The whole rock has a reddish bronze color due to the small amount of hematite and manganite it contains. Polished surfaces and thin sections show manganite replacing both the carbonates and the hematite, giving the following orders of deposition: (1) calcite-hematite-manganite-pyrolusite; (2) siderite-hematite-manganite-pyrolusite. In the brown ocherous ore manganite also replaces limonite.

Several beds of decomposed green slate contain nodules of an amorphous greenish-brown substance with a waxy luster. It occurs in botryoidal structures and has a conchoidal fracture. Similar nodules were found at the Merritt mines, and analyses show that they contain 26.53 per cent. Fe, 20.17 per cent. Mn., 0.74 per cent. CaO., and 0.41 per cent. MgO, with no alumina nor silica.[28] The nodular material effervesces slightly with cold acid, indicating the presence of a carbonate. The material is undoubtedly a manganiferous siderite and its structure is similar to the concretionary variety of siderite known as spherosiderite.[29]

Porous Manganite Ore.—The massive blocks of porous manganite ore at the Mangan No. 4 mine represent a peculiar type of ore enrichment. The ore is porous and spongy hard manganite that is produced by the leaching of silica and carbonates after the cherty beds had been but partially replaced by manganite. Many of the pores are regular in outline and connect with adjoining spaces and cavities by means of minute fractures partly microscopic in size. In this way continuous channels for the percolation of ground water were maintained. Some of the cavities are lined with crystals of manganite, or small dendritic masses of crystals project into the larger pores.

[28] Kray, Frank H., unpublished notes.

[29] Dana, p. 277.

Polished surfaces of some of the porous ore show isolated grains of quartz and calcite that have not been replaced by manganite; many fragments of such grains adjoin pores that have not been filled by manganese. The small amount of iron, shown by analysis to be associated with the manganite, is undoubtedly present in the carbonate form. Such relations suggest an early period of intensive replacement by manganite, followed by a period of leaching during which the solutions did not deposit manganese or oxidizing rather than reducing conditions prevailed and the solution cavities remained unfilled.

The masses of porous hard manganite ore favor the deposition of manganite as a replacement at a depth greater than the present depth of the ore body from the surface. In other words, erosion has removed much of the iron formation and thus the manganite that was once deposited at the water table is now in the zone of leaching and most of the quartz and carbonates have been removed.

SUMMARY OF RELATIONS OF IRON AND MANGANESE ON THE CUYUNA RANGE.

1. The development of intimate mixtures of iron and manganese oxides is shown to occur on the Cuyuna Range in the simultaneous replacement of chert by manganite and hematite; in the replacement of concretionary limonite by manganite; in the contemporaneous deposition of hematite and psilomelane in nodular concretionary ore; and in the intimate intergrowth of manganite and pyrolusite with hematite in martite crystals.

2. The high-grade Cuyuna manganese ores are mostly composed of manganite and are confined to carbonate horizons. In the unaltered state the rocks are gray-green carbonate slates, containing a higher percentage of manganese than the pink or dark, massive, ferruginous cherty horizons.

3. The soft thin-bedded limonite with concretionary manganese ore is derived from a slaty rock, whereas, hematite ore is more commonly found as a replacement of ferruginous cherts. Some of the limonite and hematite is later replaced by manganese minerals.

4. In the process of alteration of slates or ferruginous cherts into manganiferous iron ores, limonite and hematite replace the primary sedimentary minerals and they in turn are replaced by manganese minerals. However, some evidence was observed of direct replacement of gangue minerals by manganite and psilomelane.

5. In the limonitic high-phosphorus ores pyrolusite and psilomelane are most abundant and in the hematitic, high-silica, low-phosphorus ores, manganite, and psilomelane predominate.

6. The presence of manganite as the predominant manganese mineral indicates that the present ore bodies were formed by solutions from overlying portions of the iron formation that have been removed by erosion. This conclusion is supported by the fact that a résumé of the literature shows that manganite is not as abundant as pyrolusite and psilomelane in the zone of leaching, but is more abundant at greater depth.

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THE ALMADEN MERCURY ORES AND THEIR CONNECTION WITH IGNEOUS ROCKS.

R. W. VAN DER VEEN.

THE existence of igneous rocks in the immediate neighborhood of the cinnabar deposits of Almaden, Spain, has been doubted,[1] and some authors have denied their presence.[2]

Helmhacker[3] describes two specimens of rock exposed at the Universal Exposition of Vienna in 1873, the so-called "porphyry" and the "frailesca" of Almaden. The first is a diabase, probably from the dike which cuts off the San Nicolas Lode in the east. Helmhacker does not mention, however, exactly where this piece comes from. It is a fresh diabase, showing under the microscope plagioclase laths, mostly labradorite with chlorite and needles of apatite, light brown augite, ilmenite, pyrite and chlorite. Calcite and dolomite are absent. The frailesca is described as a dark gray breccia, showing a kind of "graywacke" ground mass in which occur sharp edged pieces of a light gray highly altered rock, which seems to be a diabase tuff, containing much dolomite.

Although the existence of frailesca is stated in official mine reports, no other data can be obtained. During a visit to the mine in 1916 I could not find any specimens of it underground, because the sides of the shaft, which must have been sunk through this rock, were no longer visible, nor could I find any specimens in the collections. However in the northwest part of the tenth level in the San Nicolas Lode I collected several specimens of a light gray, fine-grained rock, that in places formed the wall of the ore body, instead of the common black slate. A band of crushed

1 L. de Launay, "Traité de Métallogenie," 1913.

2 Courtenay de Kalb, "The Almaden Quicksilver Mine, with a Note on the Ore by F. L. Ransome," ECON. GEOL., Vol. XVI., Nos. 4, 5, 1921.

3 H. Helmhacker, "Ueber Diabas von Almaden und Melaphyr von Hancock," *Min. Mitth. Tschermack*, 1877, p. 753.

and folded black slate, doubtless a fault breccia, accompanied the gray rock at the contact with the ore and at the contact with the uncrushed slate. Thin sections showed it to be a highly altered eruptive rock.

During a second visit in 1919 I took care to examine thoroughly the same contact with the "porphyry" and other samples taken from this spot and from the corresponding place on the twelfth level gave the same results. All sections show a pseudo-ophitic structure. Fig. 14 demonstrates this clearly. The

FIG. 14. Section of altered diabase, twelfth level, San Nicolas lode, white, secondary silica and sericite in shape of former plagioclase; black, carbonates and pyrite. ×35. Taken from lx, Fig. 15.

former slender crystals of plagioclase have been altered to fine fibrous aggregates of sericite and secondary silica or carbonates, with secondary silica, sericite, and carbonates, (dolomite and calcite), occurring between. Pyrite is abundantly disseminated in the form of small cubes and sometimes indicates roughly the outlines of former tabular crystals, perhaps augite. Here and there colorless muscovite is developed in large elongated crystals. An opaque mineral, which seems nearly black with small mag-

nification is distributed through the rock. It shows the typical shape of ilmenite in fresh diabase. With powerful magnification, these brown patches become transparent and prove to be bunches of sagenite, with the characteristic arrangement of the needles at angles of 60 degrees. Apatite occurs in a few small elongated needles; cinnabar is visible as small rounded spots.

The analyses of this rock are similar to those mentioned by Rosenbusch [4] of an altered diabase, the so-called "white rock" (weisses Gebirge) of Holzapfel (Nassau) connected with the ore deposits of that region, and those mentioned by Lindgren [5] of an altered diabase of the North Star Mine, Grass Valley.

	Almaden Diabase.	Holzapfel Diabase.	Grass Valley Diabase.
SiO_2	39.12	36.39	45.74
TiO_2	1.14	2.46	0.36
Al_2O_3	16.63	19.63	5.29
Fe_2O_3	0.96	1.67	0.13
FeO	9.19	6.94	2.06
MgO	5.83	3.34	0.94
CaO	8.82	7.12	23.85
Na_2O	0.52	0.82	0.11
K_2O	0.38	4.82	1.92
CO_2+H_2O	18.40 ($+H_2O$)	12.61	18.91
FeS_2	1.13	0.58	

When treated with cold dilute hydrochloric acid CO_2 escapes, and iron dissolves by heating the solution indicating calcite and probably breunnerite.

The analysis of the rock is in accordance with the thin sections, and indicates sericitization and carbonatization of a diabase. Some parts show more sericite, others are more changed into carbonates. The structure of the diabase must have been ophitic. In the museum at Delft, a collection from Przibram contains several specimens of similarly altered diabase, and also of fresh diabase from the diabase dikes which are connected with the lead-silver veins of that district. Sections of these rocks are exactly similar to those of the Almaden gray altered diabase.

[4] H. von Rosenbusch, "Elemente der Gesteinslehre," p. 413, zweite Auflage.

[5] Waldemar Lindgren, "Mineral Deposits," p. 553.

Fig. 15 shows a piece of the contact of this altered diabase with the crushed slate. At the contact the gouge produced by faulting has been transformed into a grayish dolomitic substance, which is intersected by later veinlets of coarsely crystallized dolomite and quartz. Some sharp edged pieces of crushed slate remain in this groundmass. This slate breccia, containing dolomite and iron carbonate, was about one foot thick at the contact. At some distance from the contact the carbonate veinlets are less abundant.

FIG. 15. Contact of diabase with fault breccia. Calc., calcite; gr. dol., gray dolomitic rock; sl, slate; Cinn., patches of cinnabar. × ¼.

Figs. 16 and 17, representing thin sections from two different places of this contact, give a good idea of the different degrees of replacement of the fault breccia and the gouge, Fig. 17 being one foot from the contact. In Fig. 16 remnants of slate pieces are seen as dark and undefined patches. They consist of a dark colored, fine-grained carbonate substance, mingled with finely fibered silica. Small black particles of the bituminous slate substance remain and have accumulated in a flake-like form, which gives the dolomite a gray color. In other parts this coal substance has been removed more completely. Some crystals of dolomite or calcite have developed in this mass and have pushed aside the coal substance which has gathered around their borders.

Pyrite is distributed in cubes throughout the material and also in later veins of quartz and dolomite. Cinnabar occurs in minute spots and along the veinlets.

In the dolomite veinlets may be seen the so-called pinolitic arrangement of the coal particles that remained in the mass. They are pushed from the borders of the veins towards their centers. These black bands occur all along the borders of the dolomite

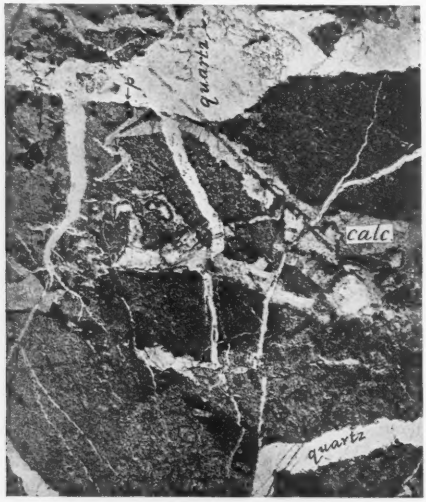

FIG. 16. Gouge breccia, section taken from 3x, Fig. 15. White, quartz veins; grayish white, carbonate in veins and fine-grained in ground mass, pinolitic structure to be seen in broader veins (crossing vertically) above calcite; black, remnants of slate in patches; p, pyrite; dolomite crystal at the left of center. × 20.

veins, in some places forming a pseudo-geode. The space in the middle is also filled by dolomite, but in different optical orientation, which is shown by the lighter color. The quartz veins are later than the dolomite veins.

In Fig. 17 some pieces of slate have been spared. The groundmass is the same fine intergrowth of carbonates and silica, with a

gray color due to the small carbon particles. Here and there crystals of calcite have developed with their characteristic black bituminous borders. A small dark spot marks the place of a former piece of slate. The triangular piece of slate shows the attack of the solutions at the base more clearly than at the top; at the base the margin has been obliterated and is only marked

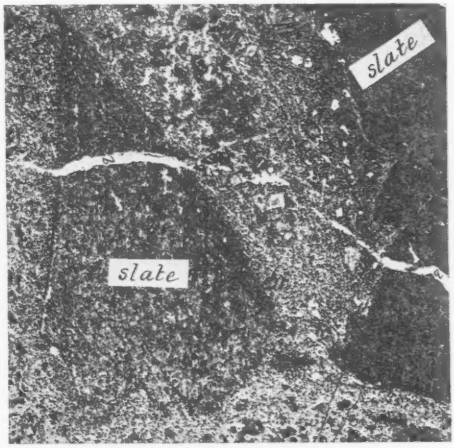

FIG. 17. Gouge breccia, section taken from piece about one foot from contact with eruptive rock. Note gradual attack of the slate. × 14.

by a seam of accumulated carbon substance. In the piece itself this bitumen has flocked together in patches. Dolomite and silica are abundant. The large piece of slate has not been much attacked and only the borders show a marked carbon seam at some distance from the unaltered material.

Both figures demonstrate on a small scale the part of replacement in vein formation, and the forming of replacement veins. Open cracks cannot have existed in this weak and plastic gouge, but the crushed zone must have been filled by fault gouge and breccia, and this material was readily attacked by the mineral

solutions. Hence the typical vein breccias, where pieces of the wall rock, or of former ore, are suspended in the vein material. We cannot assume that these pieces have been afloat in watery solutions during the deposition of the surrounding ore.

In the fault along the side of the San Nicolas Lode many well-rounded boulders of clay slate occur in the gouge, which sometimes have a diameter of one foot and more. Their surfaces are often covered with pyrite incrustations. They are of the same origin and character as those of Johann Georgenstadt mentioned by Beck.[6]

ORES.

The character of the ore has been described so fully by other authors that only a few new details may be added.

It is accepted now and proved by Ransome and others, that the deposition of the cinnabar is not a mere impregnation of porous sandstones, but that replacement has made room for the introduced minerals. The cinnabar occurs partly along small cracks in the sandstone, but in the lean ore it also follows the borders of enlarged sand particles, where it is almost always accompanied by sericite (Fig. 18).

Now we may postulate two possibilities. Either the sericite

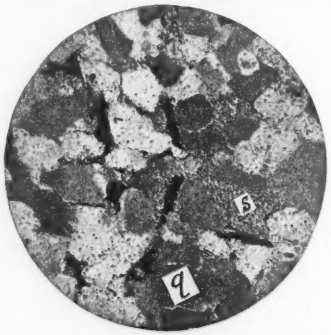

FIG. 18. Section of lean ore between X nicols. Black, cinnabar; dark and light gray (q) quartz, sericite. ×25.

[6] R. Beck, "Lehre von den Erzlagerstätten."

was already present as interstitial sericite of the quartzite and this poorly compacted sericite offered favorable channels for the quicksilver solution, or the sericitization of the quartzite is entirely or partly due to the same process as the introduction of the cinnabar. The fact that even the solid quartz grains, the clastic grains as well as the younger quartz which enlarged them, are sericiticized in the neighborhood of the ore veinlets, inclines the writer towards the second supposition.

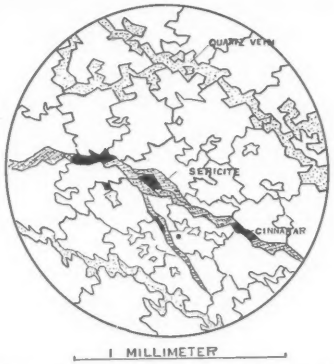

FIG. 19. Polished section of lean ore etched with HF. Borders of quartz grains are visible, the quartz veinlets are attacked differently from the sand grains, and their shape, as well as the shape of the sericite cinnabar vein shows that they are introduced later in the quartzite. × 56.

The cinnabar which was first introduced into the quartzite by small fissures found its way also through the interstitial pores of the quartzite. The younger quartz enlargements of the clastic sand grains behave optically as well as chemically like the older quartz. Where they touch, however, some capillary spaces must remain, which may be demonstrated by etching a polished section of the sandstone; the even surface which did not show any cracks or borders becomes covered with an irregular drawing of fine lines by etching with hydrofluoric acid (Fig. 19). These are the places where the quartzite may be attacked and where the solutions might have entered.

Silica was also introduced in the same manner and at the same time as the cinnabar. Fig. 19, representing the etched section of lean ore, shows quartz veins as well as sericite-quartz-cinnabar veins.

Examination of the rich compact ore, which has a steel-gray lustre, shows lighter red veins and patches running through it. This light red ore, seen in thin sections with transparent light, shows slender, colorless prismatic crystals, sometimes lying scattered in the cinnabar, often also in divergent or radiated masses and in radiated spherical concretions. (Fig. 20.) They have a

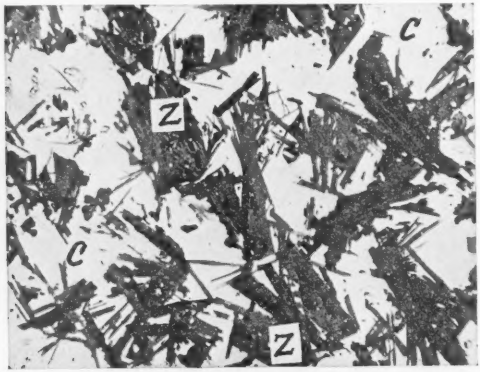

FIG. 20. Polished section of rich ore (nearly pure cinnabar). White (c) cinnabar; dark gray, zeolite. × 150.

low refraction. The micro-chemical test, after treatment with cold hydrochloric acid, gave Na. and Ca. This, combined with their optical and crystallographical character, leads to the conclusion that it is a zeolite of the natrolite group (or pectolite). This zeolite is relatively abundant in the rich ore of Almaden. Chabazite, however, which is often mentioned with the cinnabar of Almaden, I could not find.

Pyrite occurs in small quantities in the ore, sometimes in small irregularly disseminated spots, sometimes in streaks of more

considerable dimensions. Examination of polished sections shows that this pyrite is later than the cinnabar and the zeolites. It penetrates the cinnabar in veinlets and surrounds the remnants of cinnabar, which are also traversed by veins of pyrite. It is remarkable that the pyrite has not developed its own crystal form. I found only one spot where, against the totally enclosed cinnabar, the pyrite had developed cubical faces.

In the cinnabar, later removals have occurred. In the ore containing the natrolite are veinlets of pure cinnabar, sometimes with a parallel arrangement of the natrolite crystals along the borders in the older cinnabar.

CONCLUSIONS.

From Helmhacker's description of the frailesca it follows that this rock must be a breccia similar to the one above described. The only difference is that instead of crushed slate only, the brecciated material consists partly of altered diabase. This alteration seems to be of the same kind as that noticed in the contact mentioned.

The frailesca therefore does not represent a tuff, as is believed, but it is a real fault breccia, and its age is not the same as that of the Silurian sediments in which it occurs.[1] It must be older than the faulting by which it is crushed. The altered diabase of the contact I investigated is not crushed, so that it may be as old or younger than the fault. But this rock is older than the process by which it is seriticized, which must be the same which caused the mineralization of the sandstone with cinnabar. The fresh diabase at the other end of the lode has not been altered by hydrothermal processes and for that reason it must be younger than the ore-formation.

These diabases occurring close together in the ore region, and being originally of a similar structure, undoubtedly belong to one eruptive epoch, and the ore must have been deposited during the same eruptive action. Similar diabases are found near Chil-

[1] Salv. Calderon y Arana, "Rocas eruptivas de Almaden," *Anal. de la Soc. Esp. de Hist. nat.*, T. XIII., 1884.

lon and Almadenejos. Melaphyr occurs between Almaden and Gargantiel. In the neighborhood of the latter are also quicksilver deposits, already worked out.

The age of these diabases cannot be traced directly, because no rocks younger than Devonian occur in this region. The so-called ophites of the Tertiary regions on the other side of the great throw of the Guadalquivir in the ore regions of Granada, Almeria, and Cadiz, are almost the same as the diabases of Almaden. Almaden is only about one hundred kilometers north of the Guadalquivir on the "meseta," the border of which must have been cracked by the Alpine folding and intruded by Tertiary eruptives of the Betic region.

A hundred kilometers toward the north-east on the meseta is the volcanic center of Ciudad Real, with numerous basalt eruptions which intersect Carboniferous rocks. Connected with these basalts, part hydrothermal, part formed from the decay of these rocks, occur the manganese deposits in Miocene marls. Many cold springs, some containing managanese and iron, issue near these basalts and deposit manganese. There is no doubt about the Tertiary age of these eruptive rocks. The diabase of Almaden occurs in the same line parallel with the border of the meseta as the basalt above mentioned. The combination of these facts led to the suggestion that the diabases of Almaden are most probably Tertiary and that the ore deposit must be of the same age.

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PROSPECTING FOR PETROLEUM IN AUSTRALIA.

E. C. ANDREWS.

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HISTORY OF PROSPECTING.

The first great "gold rush" of Australia occurred in 1851. Many thousands of prospectors from that time onward until 1890, and even until 1900, searched the various States of Australia for commercial deposits of minerals. This search, primarily, was directed towards the discovery of gold, but other valuable minerals such as silver, lead, copper, zinc, tin, petroleum, opals, diamonds, sapphires, and platinum also were sought eagerly at the same time.

The army of prospectors that conducted this search was as competent and efficient as any other similar group of comparable size in other parts of the world; in other words, the enthusiasts who prospected Australia were the worthy companions of, or successors to, those who revealed the existence of the famous mineral deposits of South America, Mexico, the United States, Canada, South Africa, and other countries. Most of these great centers contributed materially towards the Australian contingent from their experienced group of prospectors, because of the prizes which were reported to be awaiting them in the new great field of Australia.

Many factors contributed to the efficiency of these workers. They toiled hard, and their expectation was keyed to the highest pitch as they roamed through the plateau fastnesses which extend along the whole eastern side of the Australian continent. Moreover, these men were temperamentally suited to the work. It might be said of them, as of Ulysses' men, that they "ever with a ready frolic took the thunder and the sunshine." The sight of fortunes being amassed alongside of them by the more lucky of their companions only spurred them on to greater endeavor.

And with what result did they toil? Within two years after the first find in the Bathurst district, the great goldfields of Victoria, including Bendigo, had been unearthed. Within a decade the desolate heights of Kiandra and Upper Monaro had yielded their secrets. Thence north, as far as the alluvial fields of Forbes and Parkes, finds rapidly succeeded each other. A few years later New England was prospected successfully. Then followed the finds of North Queensland and Western Australia.

This great body of prospectors—geologists in spite of themselves, pioneers of civilization, nation-builders even—it was which tracked not only the gold, but the tin deposits, in bleak New England; the tin of the tropical jungle of North Queensland, a country infested with crocodiles and savage aborigines; the tin and copper of the sodden and drenched Westland of Tasmania, a land bristling with natural difficulties and carpeted with rain forests of the worst form. These were the men who, in arid Australia, unearthed the wealth of Broken Hill and of Kalgoorlie; who found opals in the waterless country far removed from the civilization of their time; who found the sapphire and diamond fields at widely separated points; men who dared all difficulties in their feverish desire to explore the unknown and reap wonderful material rewards therefrom.

And if this group, specially fitted by temperament for this adventurous life, and recruited from the trained prospectors of the world, so unerringly led the way through trackless jungle and stony desert to the mineral wealth of Australia, a wealth

which to-day exceeds £1,000,000,000, what shall be said as to their ability to find oil or petroleum, if it should be present in commercial quantities within Australia, and if the conditions controlling its occurrence should be similar to those of other countries?

Let us look at this point slightly more in detail. These prospectors were recruited from bands of men who recognized oil in other countries. Their extra-Australian colleagues, who were no better trained in prospecting, in the course of time had located the oil fields of the great belt that half encircles Australia by way of the Malay Archipelago, New Guinea, New Caledonia, and New Zealand. They had found oil along the Tethyan Area; they had unearthed it in the Malay Archipelago; they had found it not only in Eastern America but had extended their conquests throughout Western America, in Argentina, Venezuela and the Antilles; and had even tracked the oil to its hiding places in the central regions of the United States.

The prospectors of Australia considered that oil must exist there, and that, as they had found gold, silver, and other minerals in abundance, so they also must find crude petroleum.

From 1855 onward, specimens of all sorts of decomposing animal and vegetable matter have been forwarded to various chemists, geologists, universities, and departments of mines or their equivalents in Australia.

From the plateau region of Eastern Australia, iron scums, and decomposing organic material associated with swamps or with oozes between beds of sediment, have been, and still are, sent with monotonous frequency. Many hundreds of prospecting bores for coal, oil-shale, and water have been sunk, and gas discharges from certain of them have been forwarded to Government Departments for their supposed oil contents. These gas discharges in almost every case belong to the methane and not to the wet gas series. A notable exception is the large "wet-gas" discharge from the Roma Bore. Similar material continues to be forwarded at the present time. From the arid west there has been one long succession of specimens forwarded from

cave, and other deposits, which have the appearance of an inferior asphaltic product, but which, upon examination, are found to consist of marsupial guano, representing a time when the plains held a more luxurious vegetation and supported a greater amount of mammalian life than now. They, however, are not indications of oil in commercial quantities.

The Australian public is told repeatedly that oil in abundance must and does occur within Australia, but that the Australian geologist does not appear to be alive to his responsibilities. This statement must be taken as the criticism of untrained irresponsibles of the "Get Rich Quick" type. It is much as if the following line of reasoning were adopted: Tin occurs in the great continental masses. The Archean Shield of North America is a gigantic area, and as tin occurs in Asia, Australia, South America and Western North American, so must it occur there in commercial quantities, and since the American prospector has not unearthed it, he cannot be fully aware of his responsibilities. Or it might be assumed in a similar manner that England or France should be enormous producers of gold because Paleozoic and Mesozoic rocks occur there in abundance, and these rocks in many portions of the world are known to contain gold in abundance; therefore, if the English geologists and prospectors have not found these great gold deposits that are supposed to exist there, then they are not as efficient as gold prospectors and geologists in other parts of the world.

In any case, the work of the prospector and the geologist indicates that oil, if found to exist in Australia, does not occur in the same manner as it does in countries such as America, Asia, and the East Indies, for if such were the case, it would have been found easily. The case of Peninsular India might be mentioned as similar to that of Australia. Nevertheless, the geologists of Peninsular India are doubtless as capable as geologists and prospectors in other parts of the world.

These remarks are intended to apply only to Southern and Eastern Australia. That great region extending over most of North-western Australia and described by Mr. L. J. Jones as

containing great areas of thick Paleozoic sediments dipping gently off the Archean Shield—thus suggesting a resemblance to the American Paleozoic in the oil field of Eastern North America—is only entering the initial stages of prospecting.

The following brief note furnishes the explanation for the failure to the present time in the search for petroleum.

PROSPECTING RESULTS IN INDIVIDUAL STATES.

New South Wales.—Hundreds of bores have been sunk in connection with prospecting operations for coal and water in this State. A mere trace of oil was recorded from one of these bores, namely, the Connamble Bore, at a depth of several hundreds of feet. The rocks in which the bore was sunk lie almost horizontally, and appear to be of Mesozoic age. Gas discharges from bores have been examined, but these do not appear to be of the wet gas type. Bores for oil have been sunk in Mesozoic, Permian, Devonian, and Silurian rocks, but without obtaining a semblance of commercial oil.

Victoria.—Prospecting in the gently domed or warped strata of Tertiary age, the beds of which in places are crowded with shells of various types, has yielded only negative results to date.

Tasmania.—The various boring operations in igneous and other unfavorable rock types have yielded no commercial results to date. In a recent report, however,[1] the discovery of a seepage of oil in Tasmania is announced. The locality is in the Mersey River Basin in Northern Tasmania. The seepage is recorded as a thick scum of oil covering water. It is stated that the amount of oil yielded by these seeps is too small to obtain samples for detailed testing purposes in the laboratory, but that its "oil" nature has been determined.

The oil is stated to reach the surface along a north-westerly fault plane which intersects rocks of Permian age. On one side of the fault, a seam of Tasmanite (oil shale) four feet in thickness, is exposed, and on the other side a seam of coal occurs,

[1] Reid, A. McIntosh, "Natural Oil in the State of Tasmania," quoted from the *Industrial Australian and Mining Standard*, Sept. 27, 1923, p. 473.

not exactly at the same horizon, but nevertheless belonging to the same group of rocks.

Queensland.—Roma Bore:[2] In 1900 a bore, sunk originally for water, was deepened to secure a larger flow. Gas was dis-

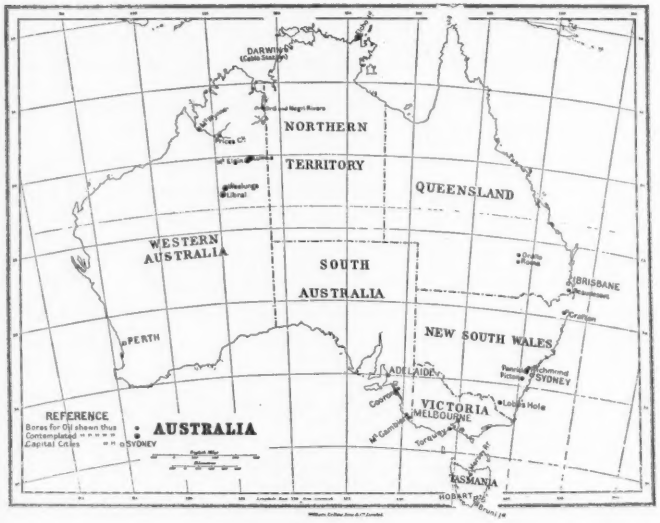

FIG. 21.

charged at a point 3,683 feet from the surface. The gas was allowed to escape for more than four years, but in 1905 the Town Council of Roma installed a Town Lighting Scheme, the gas to be supplied from the bore under consideration. The supply failed, however; the bore was abandoned for gas purposes, and used as a town water supply.

In 1907 a second bore was sunk for oil by the Intercolonial Boring Company on behalf of the Roma Mineral Oil Company.

In 1908 an abundant discharge of gas, exceeding 1,000,000 cubic feet a day, and under a pressure of 200 to 300 lbs. a square

[2] Condensed from account in *Queensland Government Mining Journal*, Vol. IX, p. 591, and Vol. 24, p. 19.

inch, was tapped at a depth of 3,702 feet. This gas was ignited by the boiler fire, and burnt fiercely for five weeks. Boring was resumed, but abandoned two years later.

In 1916, the Denham Government of Queensland undertook a search for oil. At 2,700 feet from the surface the bit broke, leaving a portion of the tool in the casing, of about 1,200 lbs. weight. It was decided then to divert the bore at a depth of 2,300 feet. This later work resulted only in the flooding of the bore, and operations were discontinued. It was considered, however, by the Government, that the occurrence of oil in the Roma district was conclusively proved, inasmuch as the wet gas discharged from the bore yielded a considerable amount of oil upon treatment.

Beaudesert: Oil was reported from this region at a depth of 85 feet. The Government Geologist of Queensland reported unfavorably, however, upon the occurrence.

Orallo (between Roma and Injune Creek): Dr. H. I. Jensen reported favorably upon the prospects for commercial oil in this district, partly because of its association structurally with Roma, and partly because he considers the geological structures are more favorable than those at Roma. In his opinion, this district furnishes an example of a mature oil-field, or one which has its oil stored within it and has not been tapped so as to give discharges from seepages at the surface.

South Australia.—Bores have been sunk, not only in Kainozoic sediments, but also in closely folded schists of Archean age.

L. K. Ward, Government Geologist of South Australia, considers that boring for oil in the South Australian districts is of too highly speculative a nature to be sound mining.

Western Australia.—In this great State, totalling 1,000,000 square miles approximately, the whole area appears to be covered with concessions for oil prospecting. These concessions appear to have been granted over geological structures without regard to age, some being wholly on Archean schists, which are closely folded, others on limestones of Tertiary age.

Junction of the Ord and Negri Rivers (Oaks' Find): Solid bituminous hydrocarbons have been seen on the surface in this area.

In the area extending over 200 to 300 miles east and west in this region, several boring operations have been conducted. At Kimberley in 1922, D. J. Mahoney, a senior member of the Geological Survey Staff of Victoria, after making an examination, considered that the Oaks-Durack-Kimberley Oil Company was justified in boring, and a site was selected for the venture.

Locke Oil Company: Mr. L. J. Jones, a senior officer of the New South Wales Geological Survey, conducted a prospecting campaign for oil in 1922 in the enormous concessional areas (50,000 to 100,000 square miles) lying to the immediate south of the concessions including Mt. Wynne, Price's Creek, and the Ord-Negri River Junction. He states:

> Carboniferous rocks occupy an extensive area in the north-western portion of Western Australia. These beds are divisible into an "Upper" or Sandstone Series, ranging up to 1,500 feet, and a "Lower" or Limestone Series (crowded with fossil remains), aggregating a thickness exceeding 1,000 feet.
>
> The Carboniferous rocks rest unconformably upon Cambrian sediments, and in places directly upon Archean granites.
>
> The Cambrian rocks are only gently flexed with local areas containing zones of more intense folding. The Carboniferous rocks are for the most part nearly horizontal with local steepening of dip up to 5 degrees forming very broad folds. Traced north and northwesterly from the margin of the Continental Shield, these beds show increased folding, gradually attaining a maximum of 27 degrees at their northern termination near Christmas Creek in the Kimberly district.
>
> Asphaltic residues and traces of petroleum had been found along the northern outcrop of the Lower Carboniferous series, and it is thought that further south, where these beds are protected by an adequate cover of Upper Carboniferous rocks, very gently flexed and free from intense faulting and fracturing, that there are possibilities of their still retaining their original oil contents.

Mr. T. Blatchford of the Western Australian Geological Survey, records the occurrence of petroleum in the Carboniferous rocks at Price's Creek, Rough Range, 28 miles S.E. of Fitzroy Crossing. In his official report to the Department of Mines, dated 28th September, 1921, he states

that "the rock formation of Rough Range is limestone . . . and is of Carboniferous geological age. . . . Mineral oil has been found in the bore, and in one instance in surface seepage."

In 1922 a further bore put down to a depth of 1,000 feet close to the site of the original borehole, yielded traces of oil.

At Mt. Wynne, 80 miles S.E. of Derby, a bore is being put down through Carboniferous rocks by the Freney Oil Company. Mr. T. Blatchford, in a report dated 7th September, 1922, on boring operations in that area, states:

> "Indications of asphaltum were seen in the bore core at 109 ft. 5 inches, and in broken strata between 118 ft. 6 in. and 121 ft. 6 in. seams of asphaltum were found filling up the joints."

A number of small springs occur on the flat close to Mt. Wynne, and one is discharging hot water (112° F.) at an estimated rate of 80,000 gallons per day.

The hot spring at its orifice forms a small pool, approximately 3 ft. long by 4 ft. 6 in. wide, which is in a constant state of ebullition with escaping gases. The gas bubbles can be seen forming in the sand at the bottom of the pool, thence rising to the top where they break rippling the surface of the pool. The discharge of gas is continuous, though variable in volume. There is a distinct odour of sulphuretted hydrogen.

Northern Territory.—The results of prospecting in this great area are only negative to date.

GEOLOGICAL STRUCTURE OF AUSTRALIA.

The Australasian region appears to have been built outward from an Archean nucleus, which forms the greater portion of Western Australia.

This region again may be divided into four zones approximately confocal with each other, namely:

(*a*) The South-western nucleus.
(*b*) The outer zone of Archean rocks passing through North-western Queensland, the Northern Territory, Southeast of Broken Hill, and possibly through the west coast of Tasmania.
(*c*) The Inland Plains of Eastern Australia.
(*d*) The plateaus of Eastern Australia.

This area is separated generally from the outlying islands to the north, east, and southeast, by deep seas. The outlying islands consist of a compound and complex zone including the Malay Archipelago, New Guinea, New Caledonia, and New Zealand.

Paleozoic and Pre-Paleozoic.—The general scheme of growth during the Paleozoic was that folding processes passed from the southwest in strips to the north, northeast, east, and southeast.

Folding action in Australia ceased with the Paleozoic, and the folding which closed the Permian affected only a relatively narrow strip extending from the Hunter River in New South Wales to the north of Queensland.

Most of the Paleozoic folding had been confined to the outer zone of islands mentioned above.

Rocks which had been developed in the zone of flowage, and subsequently exposed at the surface by denudation, are not overlain by rocks which are closely folded, and which belong to sediments of a later era. Thus the Archean sediments may be associated, in the same vertical zone or plane, with closely folded types of early Proterozoic age, but the Paleozoic types which overlie the Archean will be found to be almost unaltered, and practically devoid of folding. Similarly, schists of Ordovician age, and which evidence the action of close folding, are known to be overlain by Devonian sediments which are almost unfolded and show only slight signs of chemical alteration.

Mr. L. J. Jones has noted Cambrian Limestones from Western Australia which are almost unaltered, and which dip gently off the Archean Shield.

Maitland[8] illustrates the association of closely folded Archean with older Paleozoic, and possibly even late Proterozoic rocks, overlying them and showing only the effects of gentle folding.

Mesozoic.—The Mesozoic in Australia was one of shallow water conditions, apparently fresh water in the Trias and Jura periods in the main. An Epi-Continental sea of great extent,

[8] A. Gibb Maitland, "A Summary of Western Australia," Geol. Survey Memoir No. 1, Chapter 1, 1919. Figs. 36, 37, and 41.

but relatively shallow in depth, marked certain divisions of the Cretaceous.

Kainozoic.—The Tertiary formed a marine fringe to the continent in its southern portions.

At the close of the Tertiary, the Mesozoic and Tertiary sediments appear to have been elevated into plateaus with downwarped margins. These beds also, in certain localities, have been ornamented with very gentle undulations which may be classed as warps rather than as folds.

The Cretaceous sandstones and shales form very weak structures. The Kainozoic sands, clays, and muds, are not well compacted.

GEOLOGICAL STURCTURE OF COMMERCIAL OILFIELDS IN THE NEIGHBORHOOD OF AUSTRALIA.

Oil seepages and other surface indications of petroleum oil fields in the zone of islands mentioned above are extremely common, whether in Sumatra, Java, Borneo, Ceram, New Guinea, or New Zealand, and it would appear that this outer arc, confocal with earlier lines of fold in Australia, has been affected by Mesozoic or Kainozoic movements which have formed long lines of gentle folds in the Mesozoic and Kainozoic sediments.

Long continued geosynclines were formed in these regions on their seaward aspect. Marine sediments were deposited in these geosyclines, and they, in turn, were filled with countless numbers of minute organisms. It would appear also that portions of these geosynclines were so affected by undulatory movements of the earth's crust that there was a tendency to form rows of islands or zones of continuous land off shore, thus tending to convert the geosynclines into troughs or basins. At a later stage these sediments, filled with their micro-organisms, were again affected by earth movements, with the production of long subparallel folds, in the upper portions of which commercial oil pools were gathered.

This peculiar geological history was not at all characteristic of Australian conditions during the Mesozoic and the Kainozoic.

APPLICATION TO AUSTRALIA OF PRINCIPLES UNDER FOREGOING HEADINGS.

The geological history of Australia suggests decidedly that the conditions which controlled the formation of commercial oil pools of Tertiary age in the principal fields of the world, namely, those paralleling the curves, arcs, or zones of the Tethyan, Malayan, Antillean, and Pacific, and the Alpine and similar mountain zones, did not extend to Australia.

If crude oil fields of commercial value do exist in Australia, they apparently belong to formations older than the Tertiary.

The history of prospecting for oil in Australia indicates that this great region is comparable somewhat with Peninsular India, which has not yet been proved to contain commercial oil, but which is bound on the northwest, north, and east by the great curving zones of the Tethyan area in which commercial oil pools are found.

South Africa also furnishes a parallel to Australia in that it has yielded no commercial oil, but is paralleled far to the north by the zone of Tethys with its oil fields.

South America does not furnish a case parallel to Australia, for in that great country the Pacific girdle of Kainozoic mountain uplift does not stand well off shore as is the case with Australia, but sweeps clean through the whole of the Andean tract, and throughout the Antillean Curve to Venezuela. The bitumen fragments found in the rock joints along the Negri River in Western Australia, the reported oil seeps in the Mersey Basin in Tasmania, the discharges of wet gas from the Roma Bore, and the very gentle dip off the Archean Shield of the Lower Carboniferous limestone of highly fossiliferous nature in Western Australia, the latter as reported by Mr. Jones, are all possible indications of the occurrence of oil in Australia, but not necessarily of a commercial nature.

If we may judge by the experience of oil prospecting outside Australia, the value of the expectation of securing crude petroleum in commercial quantities within the area under consideration is small and is not to be considered as a business proposition by small investors.

SYDNEY, AUSTRALIA.

A STUDY OF THE SUDBURY ORE DEPOSITS.

ALFRED WANDKE AND ROBERT HOFFMAN.

MAR 10 1924

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INTRODUCTION.

Foreword.—The origin of the ore deposits of the Sudbury district has been a matter of discussion for many years. Three leading hypotheses of origin have been advanced,—(1) magmatic differentiation in situ; (2) high temperature hydrothermal replacement; (3) injection of molten sulphide. The following paper is based upon field visits and laboratory study of thin and polished sections made from specimens which represent cross sections of the nickel eruptive and the mineralized rock types and ores from several contact and offset deposits. A type of rock alteration consisting of hornblende, biotite, albite, and quartz is recognized as characteristic of the district. This affects all rocks associated with ore but is best seen in the mineralized granite of the Creighton mine. We conclude that rock replacement is a vital factor in the emplacement of these ores and that the type of

replacement is indicative of high temperature and pressure. We also conclude that the ores were not derived from the immediately adjacent norite but came, perhaps, from the same parent magma of which the nickel eruptive is an offshoot; that the ores are persistent with depth; and that ore bodies may be found that do not outcrop.

Acknowledgments.—We find ourselves indebted to several whose kindness and courtesies we wish to acknowledge. Permission to visit the underground workings was granted us by the operators of the district whenever asked for and they also lent assistance in many ways. We desire to express our thanks for special favors to Mr. Hubbard and Captain Roscoe of the Murray mine, to Mr. Eager of the Levack mine, to Mr. Carmichael of the Worthington mine and particularly to Mr. J. C. Nicholls and his staff of the International Nickel Company. Mr. Nicholls placed at our disposal a vertical section and a generalized plan of the 20th level of the Creighton mine and also granted us permission to publish certain geological relationships that had been worked out by his staff. To Mr. G. S. Scott formerly of the Internation Nickel Company we owe much for his coöperation and the unselfish way in which he placed material of his own collecting at our disposal. Mr. P. G. B. Gilbert, one of our colleagues, has given us the benefit of his knowledge of the district and checked up several of the details of mineral relationship. The work has been carried out in the laboratory of economic geology of Harvard University and we take pleasure in expressing our thanks to Prof. L. C. Graton whose interest has stimulated this investigation.

General Geology.—The Sudbury district of Ontario, Canada, made classical by the careful study of several members of the Canadian Geological Survey, requires perhaps no more than a brief sketch of the general geology. The most important rock is the nickel eruptive described by A. P. Coleman[1] as a huge sheet of norite-micropegmatite, that is the outer margin of this sheet is norite and it grades toward the center into a rock of

[1] "The Nickel Industry," 1913.

granitic composition characterized by micropegmatite. The eruptive occurs as a body of oval outline measuring 36 by 15 miles and having a thickness in the outcrop of from 1 to 4 miles. It may best be described as a spoonshaped sill which along its northwest margin dips gently to the southeast but along its southeast margin it dips quite steeply to the northwest. The bowl of this spoon is filled with about 9,000 feet of sandstone, shale, and conglomerate of Upper Huronian age. The sill rests upon eruptives of Keewatin, Grenville, and Laurentian age and sediments, called by Coleman the "Sudbury series," consisting largely of crystalline limestone, quartzite, schist and gneiss. The entire thickness of this rock series is about 30,000 feet. In the basic eruptives there are gabbros, norites, and greenstones, the latter being in part modified volcanics. About the lower contact of the nickel eruptive there is also found granite and granite gneiss which form the footwall of some of the ore bodies. These granitic rocks are classified as Laurentian, are intrusive into the "Sudbury series" but are older than the norite of the sill. Near the Murray mine there is an occurrence of granite that intrudes[2] the norite. Later than the nickel eruptive are diabase and norite dikes as well as a few granitic dikes.

Ores.—The ores in general consist of about two parts of nickel to one of copper and average between three and four per cent. in total nickel and copper content. Although copper and nickel are the chief metals, platinum, silver, palladium, and osmium are also recovered. The principal metallic minerals in the ore are magnetite, pyrrhotite, pentlandite, and chalcopyrite; ilmenite, pyrite, sphalerite, galena, molybdenite, sperrylite, arsenopyrite, gersdorffite, and polydymite are rather rare constituents.

Production.—Detailed figures covering the total production are not available but assembling those given in various publications the total for the district to date appears to have been a little more than 15 million tons of ore that would average from 2–4 per cent. nickel and 1½ to 3 per cent. copper. The reserves of the district are large, the available figures indicating about 100

[2] C. W. Knight, "Nickel Deposits of the World," Toronto, 1917.

million tons of ore slightly lower in grade than that already mined.

Origin.—The origin of these ores has been a matter of geological discussion for the past 30 years and the end seems not yet in sight. Bell,[3] one of the earliest workers in the field, evolved the theory of magmatic segregation. That is, the ore minerals were an essential part of the original nickel eruptive magma at the time of its intrusion and through gravitative differentiation settled into hollows and bays at the base of the nickel eruptive. This theory has been advocated by other workers in the same and similar fields among whom may be mentioned Barlow, Adams, Browne, Kemp, Vogt, Daly, Goodchild, and particularly Coleman to whom many of the details and facts of ore occurrence in this district are due. Recently, in 1918, Roberts and Longyear[4] subscribed to this theory of magmatic segregation in situ. About 1903 C. W. Dickson[5] studied the mines and on the basis of microscopic and field work attacked the magmatic theory assigning to the ore bodies a hydrothermal or pneumatolytic origin. Collins, Posepney, Emmons, Bush, Argall, Beck, Knight and Campbell have expressed essential agreement with Dickson as to the origin of the ores. Other students of ore deposits attracted by the problem began to see that certain facts of both sides of this controversy were right and in attempting to harmonize these facts evolved theories of origin that modify either the differentiation hypothesis or the hydrothermal hypothesis. Howe[6] thought that the sulphides seemed actually intruded into the enclosing rock and considered differentiation to have taken place in depth and that the ores were later emplaced by a process of sulphide injection. Tolman and Rogers,[7] after a study of specimens from this and what they considered to be other similar deposits, state,

> We disagree with Dickson as to the hydrothermal origin of the ores. We agree, on the other hand, with the supporters of the magmatic hypoth-

[3] *Bull. Geol. Soc. Amer.*, Vol. 2, 1890, pp. 125–137.
[4] *T. A. I. M. E.*, Vol. 59, 1918, p. 56.
[5] *T. A. I. M. E.*, Vol. 34, 1904.
[6] Econ. Geol., Vol. 9, 1914.
[7] Leland Stanford Jr., Univ. Pub. Univ. Series, 1916.

esis that the ores were formed in the magmatic period. They were not formed in the early stage and not by the sinking of the sulphide constituents. . . "Also the ores are believed to be magmatic. They have been formed at the end of the magmatic period by the replacement of silicates."

Later, Prof. Alan M. Bateman [8] took up the discussion. He believed in the magmatic segregation of the ores with magmatic segregation taking place for the most part in the magma reservoir; that the sulphide magma after differentiation was intruded in much the same manner as any igneous rock; and that later hydrothermal action modified the deposits. In 1920 the staff [9] of the International Nickel Company published an article dealing with the mining and smelting operations of the International Nickel Company. Their observations lead to the following conclusions.

Geological work at the mine has disclosed facts that indicate the origin of the ore by its intrusion in molten condition along a plane of shearing in the foot wall rocks adjacent to the norite, after the latter had solidified. The most interesting evidence is offered by a dike of comparatively fresh younger norite that intrudes the main body of the norite and its foot wall rocks. It is itself intruded by the ore and also altered by it. The rock alteration is an unusual variety of contact metamorphism. It appears as a dark margin of varying width from a quarter of an inch to six inches against the ore. It is found in every rock with which the ore comes in contact, except the diabase dikes which are younger.[10]

Thus the staff of the International Nickel Company subscribes to the views of Howe and Bateman that the ore is a type of molten sulphide injection. In the October, 1920, number of ECONOMIC GEOLOGY, Prof. W. Lindgren adds a word of discussion to the origin of these ores. He believes that the deposit represents an injection of molten sulphides.

Without going into details and reasons, it may be well at this place to indicate that the authors believe the ores to be high

[8] ECON. GEOL., Vol. 12, 1917, p. 391.

[9] *Canadian Inst. Min. Met.*, March, 1920.

[10] Credit should be given to Mr. G. S. Scott formerly geologist of the International Nickel Company for being the first to recognize this distinctive type of rock alteration and also for working out the geology which points to the relatively late time of formation of the Creighton ore bodies.

temperature replacements along zones or belts of shearing and brecciation. Neither sulphide injection nor magmatic segregation in situ seem to account for the ore bodies.

Reason for Study.—Active mines constantly furnish new data to be applied in the deciphering of the geology of a given deposit. Some of the mines of the Sudbury district now having attained a depth of over 3,000 feet, it seemed to us that a comprehensive study of the intrusive nickel eruptive and many of the associated ore deposits might add new facts which would shed additional light upon the genesis of the ores.

Extent of Study.—During the summer of 1920 Mr. Hoffman spent a week in the Sudbury district. Under the guidance of Mr. G. S. Scott specimens were collected from the nickel eruptive and the Creighton mine. The specimens of ore bearing granite from this mine showed the Sudbury type of rock alteration in a striking way. These specimens moreover suggested that this type of rock alteration might be general and if so was strongly indicative of a high temperature replacement origin of the ores. With this view in mind Mr. Wandke spent two days in the Sudbury district in September, 1920, and a number of specimens were collected from the 18th and 20th levels of the Creighton mine. During the collecting the questions of rock alteration and the emplacement of the ore were given particular attention. After a laboratory study of the specimens Mr. Hoffman again visited the district in the fall of 1921 for a week and collected material from several other mines in order to carry on the comparative study, and to check up some of the earlier observations. The deposits were also visited at this time by Prof. L. C. Graton and Mr. B. S. Butler. Their collection from the Levack mine gave us some excellent material for this study. Mr. G. S. Scott, then geologist for the International Nickel Company, again gave Mr. Hoffman the benefit of his intimate knowledge of this district. He later sent us some rather choice specimens from the Levack ore as well as a suite of specimens illustrating the Onaping-Windy Lake section. In 1922 Mr. P. G. B. Gilbert collected material underground from several of the mines of this

district. His independent notes and collections enabled us to check our observations and deductions regarding the rock alteration.

Our study has embraced the examination of some 300 thin and polished specimens representing ore and rock specimens from ten mines and three cross sections from the basic to the acid edge. The mines represented are the Creighton, Frood, Stobie, Crean Hill, Copper Cliff, Levack, Murray, Garson, Falconbridge, and Worthington. The cross sections represent the Creighton-Lake Emma, Murray-Azilda, and Onaping-Windy Lake sections. Thus the various types of deposits as well as the nickel eruptive were represented by a good many specimens.

PETROGRAPHY.

The Nickel Eruptive.—By many petrographers this intrusive body has been pointed out as an illustration of magmatic differentiation. Gradations can easily be followed from dark-colored basic-appearing rock at the outer margin to light-colored granitic-looking rock 2½ to 3 miles from the peripheral contact. The contacts are such as to suggest that the intrusive body is a laccolith. Magmatic differentiation under gravitative control has been appealed to in order to explain the field relations. Our study did not permit of the time to thresh out the field relations and little confirmatory evidence regarding the laccolithic nature of this body was obtained. At the Creighton mine where considerable deep drilling has been carried on, the contact between the nickel eruptive and the older rocks still has approximately the same angle (45°) of inclination at a depth of 3,500 feet as characterized this contact at the surface. This rather flat angle of dip of the contact for a mine near the middle of the ellipse contrasts with the steep angle of dip for a mine near the end of the ellipse such as the Falconbridge, where the contact actually dips away from the eruptive. These conditions at the contact are cited merely to call attention to the complexity of the details associated with the intrusive relations of this eruptive.

Our field work confirms the various statements made regarding

the differentiation [10b] of this intrusive. The transition although locally marked by abrupt variations in color and mineral composition, takes place in a broad way by a gradual change in mineral composition, wherein, in passing from center to margin potash and soda-lime feldspars and hornblende give way to lime-soda feldspar and pyroxene. These changes in composition are rather well shown in Table I, a composite of our three cross-sec-

TABLE I.

Mineral.	Distance in Miles from the Basic Edge.								
	.01	.1	.2	.4	.6	.8	1.2	1.6	2–2.7
Olivine		×							
Magnetite	×	×	×	×	×	×			
Hypersthene	×	×	×	×		×			
Pyroxene	×	×	×	×					
Hornblende	×	×	×	×	×	×	×	×	×
Biotite	×			×	×	×	×	×	×
Labradorite	×	×	×	×					
Andesine	×			×	×	×	×	×	
Oligoclase							×	×	
Albite								×	×
Micropegmatite		×				×	×	×	×
Microcline									×
Orthoclase									×
Quartz	×	×	×	×	×	×	×	×	×
Magnetite							×	×	×
Apatite		×	×	×	×	×	×	×	×
Pyrrhotite	×	×	×	×	×	×	×	×	×
Pyrite								×	×
Pentlandite	×	×	×	×	×	×	×	×	×
Chalcopyrite	×	×	×	×	×	×	×	×	
Specularite								×	

tions, which lists the essential minerals and the chief accessories, but not the alteration products.

Not only does a gradation from a femic to a salic rock type characterize the intrusive but the mineral alteration is also striking. In almost every thin section the primary minerals can be seen to have altered, some more so than others. The magnetite almost invariably has a bordering rim of biotite or else is fairly well altered to titanite and rutile. As distance from the lower

[10b] First described by T. L. Walker, Quat. Jour. Geol. Soc., London, Vol. 53, 1897.

contact is gained the magnetite becomes more and more altered. The hypersthene has usually changed to bastite and the monoclinic pyroxene rather completely to uralite and actinolite which in turn give way to biotite. The primary hornblende, a green variety, alters to flake biotite,[11] blue-green hornblende,[12] quartz and a carbonate. Within the hornblende are rod-like grains that have partly changed to rutile, which suggests that the hornblende carried included ilmenite. The biotite may recrystallize to flake biotite or alter to chlorite. The plagioclase alters to and is veined by chlorite, calcite, flake biotite and blue hornblende, or by epidote, zoisite and calcite. Occasionally the plagioclase is recrystallized to quartz, albite, and orthoclase. In interstitial areas associated with quartz, chlorite, calcite, and albite, are the sulphides pyrrhotite, chalcopyrite, and sphalerite. With the quartz in similar areas are found blue hornblende and rarely tourmaline.

From about one mile inward from the basic edge and extending from there to the central oval of Upper Huronian sediments is a zone from one to three miles wide consisting of coarse-grained rock which grades from quartz diorite or granodiorite to a rock having the mineral composition of a granite and characterized by micropegmatite. The rock of the outer or more basic portion of this zone has as essential minerals plagioclase (variety andesine), hornblende, biotite, magnetite, and quartz. Apatite forms the chief accessory mineral. As the rock becomes lighter in color the feldspar and quartz become more abundant. In the granitic rock soda-potash feldspar and orthoclase are dominant minerals. Micropegmatite is invariably present in this zone. Pyrrhotite is still present but the proportion of pyrite has become greater even though the total amount of the sulphides is considerably less.

[11] Biotite occurring as minute foils, either in veins or in aggregates, has been called flake biotite to distinguish it from the large plates of early biotite. This flake biotite seems to be a pneumotectic mineral.

[12] The blue-green hornblende, frequently mentioned throughout this paper seems to be a variety of actinolite. It is most abundantly developed just ahead of the sulphides. Mr. Ernest Fairbanks, student Harvard University, made the following optical determinations of this mineral. Opt. character plus; elongation minus; pleochroism: γ, deep greenish blue; β, deep yellowish green; α, pale yellow; extinction $14 + °$. Indices of refraction: $\gamma = 1.700$; $\beta = 1.685$; $\alpha = 1.679$.

Alteration is marked in the rocks of this zone, thin sections showing not only abundant secondary minerals but also the effects of a decided shearing. The chief secondary minerals are albite, blue-green hornblende, flake biotite, zoisite, epidote, calcite, quartz, sericite, chlorite, titanite, and rutile. Among the sulphide minerals present are pyrrhotite and pyrite with the pyrite more abundant in the upper parts of the sill. The plagioclase alters characteristically to albite, sericite, epidote, zoisite, calcite and chlorite. Some of the plagioclase alters on its outer edges to microcline. The hornblende alters to blue fibrous hornblende or flake biotite and quartz. Of the various primary rock constituents the hornblende is most susceptible to replacement by the sulphides. The biotite either alters to chlorite (suggesting clinochlorite) or is recrystallized into a multitude of minute scales or flakes of biotite which in turn alter to chlorite. The magnetite is usually rather well altered to titanite or rutile. In the minute veinlets which are present in all thin sections examined are found as the chief minerals quartz, albite, orthoclase, calcite and epidote. The sulphide minerals where present occur in intersertal areas intimately related to quartz, calcite and chlorite.

The changing mineral succession as listed in the preceding paragraphs has often been noted in the literature. The alterations which these early formed essential minerals undergo has been given but scanty attention. It seems probable that mineral alteration began about as soon as rock crystallization was well under way and ended shortly after complete consolidation had been effected. The stage in this alteration characterized by such minerals as chlorite, blue-green hornblende, biotite, albite, zoisite, epidote, calcite, quartz, sericite, pyrite, pyrrhotite, chalcopyrite, and sphalerite undoubtedly marks the effects of the mineralizers liberated during the later stages of rock consolidation and in a miniature way is taken to represent a general although slight attack upon the rock by solutions which resembled those that later deposited great masses of sulphide.

As a summary of the study of these sections, the following conclusions are presented.

(1) The primary nickel eruptive magma was a medio silicic melt having the average composition of a quartz diorite.

(2) After intrusion differentiation took place, the net result being to produce near the contact of the eruptive with the underlying rocks a quartz-norite or quartz gabbro, which away from the contact grades through quartz diorite to granite.

(3) The heavier molecules settled out gravitatively. These went to form pyroxene, olivine, magnetite, and the sulphides. The lighter molecules which later formed the quartz, soda and potash feldspars, floated upward.

(4) After crystallization had begun, the earlier formed minerals became unstable and new minerals resulted producing new rock phases. This is particularly well shown where the change of pyroxene to amphibole marks the passage of gabbro to diorite.

(5) After practically complete consolidation the mineralizers were liberated in abundance and also produced rock alteration. Apatite, blue hornblende, biotite, chlorite, albite, quartz, calcite and the sulphides are characteristic of this period.

(6) In the lower portions of the sill pyrrhotite is the characteristic and dominant sulphide, whereas in the upper or acid differentiate pyrite is almost as abundant. This change in the sulphides, ferrous sulphide (pyrrhotite) in the lower parts of the sill to pyrite in the upper parts of the sill seems related to the abundance of ferrous oxide (magnetite) in the lower parts of the sill and the alteration of this magnetite with the production of a little hematite in the more acid parts of the nickel eruptive.

From the foregoing statements it is possible to picture an orderly sequence of events within a single magmatic mass which was unaffected by marked additions of material from an outside source. The sequence would be: (1) intrusion of the nickel eruptive magma; (2) early crystallization, the minerals formed being affected by gravitative adjustment; (3) intramagmatic mineral alteration corresponding perhaps to the reactive period of Bowen; (4) concentration of the volatile components during the process of crystallization; (5) mineral alteration with hydrous and alkaline minerals being formed; (6) consolidation of

the magma the process of crystallization being practically completed; (7) high temperature and pressure mineral alteration due to the escaping volatile components and corresponding to the pneumotectic period; (8) final lower temperature mineral alteration serpentine being one of the last minerals to form. It is to be remarked that although magmatic differentiation has produced a decided difference in rock composition as regards the outer and inner portions of this igneous body, our specimens and sections fail to show any notable or impressive segregation of such heavy minerals as magnetite and the sulphides in the outer or basic portion of the intrusive. The following table showing the amounts of iron oxides and sulphides in different parts of the nickel eruptive as reported by various analysts gives an approximation of the amount of differentiation.

	Fe_2O_3.	FeO.	Totals.	Sulphur.[14]
Creighton mine [13]				
140 feet NW of open pit	2.32	8.03	10.35	
200 feet NW of open pit	2.51	8.19	10.70	
Basic edge				.54
2,000 feet NW of open pit	3.35	5.72	9.07	
Murray mine				
30 feet NW of basic edge	3.36	7.02	10.38	
150 feet NW of basic edge	1.82	6.67	8.49	
1,200 feet NW of basic edge	4.90	5.88	10.78	
1,900 feet NW of basic edge	2.26	5.28	7.54	
Onaping section				
Acid edge				.19

[13] Rept. Ontario Nickel Commission, 1917, pp. 118–119.

[14] Coleman, A. P., "The Sudbury Nickel Field," 1905, p. 116.

These analyses show that there has been a slight concentration of iron oxide in the lower contact portions of the sill as compared with rock material 2,000 feet from the contact. The change in the amount of sulphur in basic and acid rock is also in keeping with the amount of sulphide visible in the hand specimens. The sulphur is combined with iron, copper, nickel, and zinc as the abundant elements. Of these all but the iron are present in the norite away from ore in traces or at most as a few one hundredths of one per cent. It is difficult to say without experi-

mental work whether or not the norite was saturated by this minute percentage of sulphide at the time of its solidification. The microscopic study of the rock indicates that the sulphides were held in solution by the mineralizers and so experimental work upon a dry melt would hardly give satisfactory results in trying to answer this question of saturation. Had the ore bodies been due to magmatic segregation it seems probable that a much more gradational boundary would exist between ore and waste than is now the case. In the Creighton mine, for example, one passes from ore to waste in the space of a few feet and not in tens of feet as a magmatic segregation hypothesis would imply.

Associated Rocks.—Associated with the nickel eruptive and having an important bearing upon the question of rock alteration in connection with the development of the sulphides are several rock varieties. Among these are granite, younger norite, greenstone, quartzite, uralitic diabase. Granite forms the foot wall of the Creighton ore body and is also found at several points along the margin. In it are found the ores of the Levack mine. "Norite" dikes occur cutting not only the main norite mass but also the granite and greenstone, being in turn cut by the uralitic diabase dikes. The "norite" dikes prove to be quartz diorites and in places, such as the offset deposits, have notable amounts of ore associated. The greenstones are presumably in part basic effusives altered by the intruded granite, and then further altered by the ore solutions. Quartzite under the influence of contact metamorphism may become completely recrystallized to coarse opalescent quartz and is then easily mistaken for gangue material deposited by the ore solutions. The uralitic diabase dikes are the youngest rocks in the vicinity of the mines and where found are seen to be cutting the ore bodies and the associated rocks.

All of the above mentioned rock types are easily recognized in certain specimens that have undergone but slight alteration. Where shearing is pronounced, or where ore mineralization has particularly affected the rock its original nature can be made out only with difficulty, and indeed confusion may easily result as to what is altered and what is not. For the present study an at-

tempt was made to obtain a complete gradational suite of several rock types so that the various changes from fresh to highly altered rock might be observed. Care was taken to give each specimen its proper field name and location as regards proximity to ore because so complete has been the alteration of the various rock types that from a single thin section it would in many cases be next to impossible to say what the original rock was. Merely a beginning has been made on many of the problems relating to these deposits and their final solution will demand much more detailed field work.

The Ore Bodies.—Our belief is that the ore bodies occurring about the nickel eruptive form a unit. Any explanation offered for one of the deposits must also explain the others. Coleman considers these deposits from their marginal relationship to the nickel eruptive and it seems to us to call attention to a point that should not be lost sight of. In the following detailed remarks the ore bodies are treated as nearly as possible in the order of their nearness to the outer contact of the eruptive to facilitate later comparisons.

Creighton Mine.—Most of the published statements regarding this remarkable ore body were made before the mine had attained a depth of more than 1,000 feet. In the upper workings the ore occurs at the contact between the norite and the granite. At about the 12th level the ore body swings away from the norite contact and is entirely in the granite and greenstone and at least 200 feet from the contact. In fact at the 20th level a second ore body occurs between the main ore body and the norite. Thus the main Creighton ore body described as the typical marginal occurrence of ore becomes a parallel offset deposit in the lower workings. (See Fig. 22 *a*.)

The 20th level is a particularly favorable place for studying the occurrence of the ore. This level starting at the shaft in the granite cuts both of the ore bodies and passes beyond the contact for several hundred feet in the norite. Along this level may be obtained specimens of granite, greenstone, uralitic diabase dikes, "younger norite," mineralized norite and fresh norite. Our

specimens illustrate all of these various rock types. (See Fig. 22 *b*.)

The oldest rock in these workings is the greenstone. This in part was at one time a basic rock, perhaps a basaltic effusive that was altered on being intruded by the granite; hornblende rather than chlorite was developed in abundance, making up more than 50 per cent. of the rock so that the rock may well be termed an amphibolite. In addition there is also present fine-grained granular andesine, perhaps representing recrystallized original feldspar, a little biotite, magnetite, apatite and zoisite. Where the

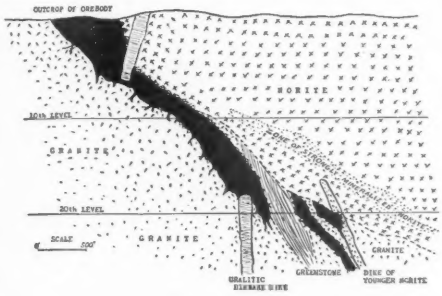


FIG. 22 *a*.

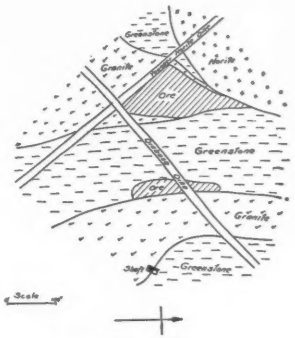


FIG. 22 *b*.

FIG. 22. Creighton Mine. *a*. Generalized geological section. *b*. Generalized geological plan of the 20th level.

sulphides occur, biotite becomes more abundant and quartz and albite are also developed. The sulphides invariably replace the femic minerals.

The granite about the Creighton mine is clearly younger than the greenstone. Practically all of it, however, is slightly gneissoid in appearance and has a crystalloblastic texture under the microscope. Both light and dark phases of granite are common and at one place upon the 20th level a thirty foot band of aplite cuts the coarser varieties. The aplite is fractured, and carries in these fractures the ore sulphides. It did not cut the ore body. The coarse slightly gneissic granite is undoubtedly earlier than

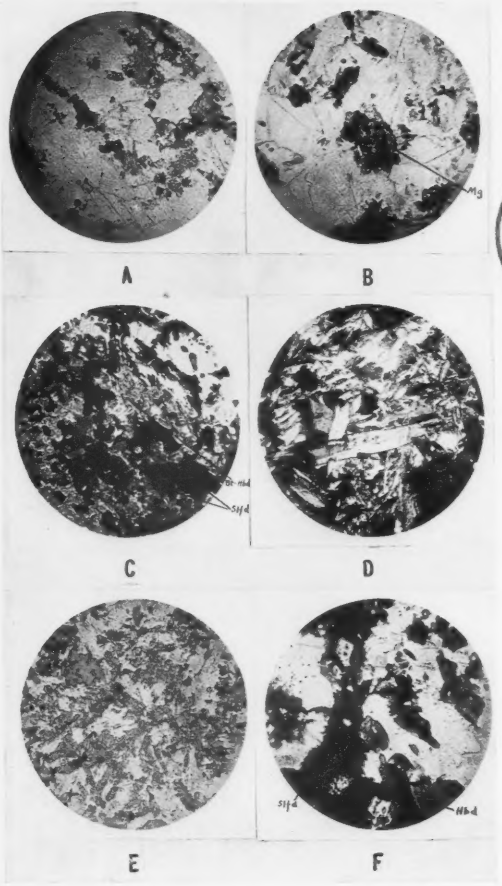
the norite of the nickel eruptive and so also may be the aplite.[15]

The ordinary coarse granite is a typical biotite granite although in its darker phases hornblende is an abundant mineral. The biotite as seen in thin section is frayed and ragged in appearance, evidently a result of shearing. Away from the ore the feldspar, particularly the soda-lime feldspar, carries chlorite, sericite, epidote, zoisite, and calcite. Near the ore hornblende and biotite with granular albite and quartz become increasingly abundant. In the ore bodies angular blocks of granite abound along the foot side. Each of these blocks shows a black rim of hornblende and biotite which separates the unaltered granite[16] from the encroaching sulphides. The relations can be seen with unusual clearness underground and are also well brought out in drill cores from the ore bodies. Thin sections of selected specimens show the various stages of this type of rock alteration and replacement which, in its end phases, causes granite to resemble altered greenstone or norite.

The hanging wall norite is a dark-colored basic rock of medium to coarse grain. The long exploratory crosscut on the 20th level permits this rock to be studied for several hundred feet from the contact. Our thin sections show little change in the character of the norite in the 900 feet of drifting which they represented. The rock is a slightly sheared quartz norite showing as primary minerals labradorite, hypersthene, diallage, hornblende, biotite, magnetite, apatite, quartz and the sulphides. As secondary minerals there are present blue-green hornblende, actinolite, sericite, epidote, titanite, quartz, calcite, chlorite, pyrrhotite, pyrite, pentlandite, chalcopyrite and sphalerite. The sulphides are in large measure classified as secondary minerals rather than as primary original constituents of the norite magma. The reasons for so doing are, (1) that they in all cases occupy interstitial spaces and

[15] C. W. Knight, Nickel Deposits of the World, mentions some of the granite about the Creighton mine as younger than the norite. Our work did not attempt to settle this problem.

[16] For a similar occurrence see R. Beck, "Die Nickelerzlagerstätte von Sohland," *Zeit. der d. geol. gesell.*, Vol. 55, 1903, p. 325. For a similar relation of biotite and hornblende to sulphides see E. Howe, "Sulphide bearing rocks from Litchfield, Conn.," ECON. GEOL., Vol. 10, 1915, pp. 330–347.



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A. Dark granite typical of foot side of Creighton orebody; unmineralized. × 28.

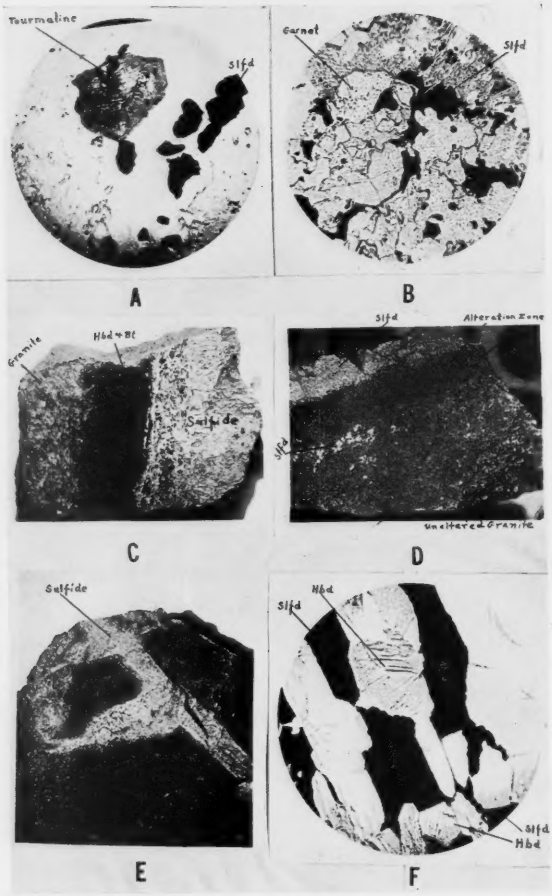
B. Early alteration of rock similar to *A*. Magnetite (Mg) is accompanied by biotite and hornblende. × 28.

C. A more advanced stage of alteration than *B*. Granite is almost completely replaced by hornblende (hbd), biotite (bt) and the sulphides (slfd). × 28.

D. Granite completely replaced by hornblende, biotite and sulphide. × 60.

E. Typical quartz diorite (younger norite). This dike rock cuts the nickel eruptive and is mineralized. × 28.

F. Quartz diorite dike at Worthington mine replaced by sulphides (slfd), biotite, and hornblende (hbd). × 28.



A. Tourmaline from Crean Hill mine associated with sulphides. × 60.

B. Garnet from the Stobie mine intergrown with and replaced by sulphides (slfd). × 60.

C. Granite from 18th level of Creighton mine being replaced by hornblende, biotite and sulphide. Black alteration band is typical of Sudbury rock alteration. Natural size.

D. Granite from the Creighton mine showing the characteristic alteration band. Natural size.

E. Brecciated beerbachite dike cemented by sulphide. This dike cuts the norite and the granite. ½ Natural size.

F. Sulphide (slfd) replacing blue-green hornblende. × 60.

are later than the primary silicates; (2) between the sulphides and the primary silicate that is being replaced there is developed in almost every instance a little blue hornblende and biotite; (3) undoubted veins of sulphides at least 200 feet from the contact are found cutting the norite; (4) in the vicinity of the veins the norite becomes spotted with sulphide; (5) the rock alteration would indicate that the norite along this contact had been traversed by solutions; (6) near the contact a dike of quartz diorite (younger norite) cuts the norite of the nickel eruptive; (7) this dike of quartz diorite is veined and replaced by sulphides thus indicating the sulphides in part at least, to be younger than a period of dike intrusion.

The "younger norite" has as essential minerals, plagioclase (andesine to labradorite), hornblende, biotite, quartz, and apatite. It is noteworthy that magnetite is practically absent in the unaltered phases of this rock. Its former presence is, however, indicated by the patterns of the grains of titanite, in which a little residual magnetite is still to be seen. Both hornblende and biotite, although frayed and yielding rutile as an alteration product, are partly recrystallized, the former to granular hornblende, the latter to flake biotite. The plagioclase has altered in part to sericite, epidote, and calcite.

Cutting the greenstone, granite and norite is a dike rock called beerbachite, which in thin section is seen to be composed of andesine and labradorite feldspar and pyroxene as the essential minerals. As accessories one may see apatite and a little biotite. Where sulphides occur, fibrous blue hornblende is abundant. An excellent exposure of this rock was to be had in the No. 8 pillar stope of the 18th level. The rock had been shattered, the brecciated texture being brought out with great clearness by the veins of sulphides. In the hand specimen the rock seems to be quite unaltered close to the sulphides, but thin sections establish the usual biotite-hornblende type of alteration. In this instance a dike rock, which cuts the norite, greenstone and granite and is itself mineralized, can be seen in a stope in the footwall of the nickel eruptive about 400 feet away from the contact. The

occurrence gives added proof that the period of ore deposition was not immediately related in time to the consolidation of the main nickel eruptive and hence indicates that straight magmatic differentiation in place could hardly have been operative in forming the ore bodies, and would also tend to show that the ores do not belong to the magmatic period as defined by Tolman and Rogers.

Several dikes that have been called uralitic diabases cut the ores and the norite, granite, and greenstone. Our thin sections show these dikes to be quartz diabase dikes and quite similar in many respects to the dike of "younger norite" described above. Against the ore, these dikes are very fine grained [17] and almost glassy as though the sulphides by rapidly conducting away the heat of the intrusive had caused a quick chilling.

A study of the polished sections of the silicate rocks indicates that there are two distinct ages of magnetite, the one related to the period of rock crystallization and usually found as irregular crystals partly resorbed and usually altered, surrounded by hornblende and biotite; the other introduced into the rock along with the sulphides preceded all but the pyrite. The latter type generally occurs as slightly rounded or euhedral crystals in the sulphides. Since the later magnetite is present as microscopic and megascopic crystals there is a suggestion that this oxide of iron was resistant to the sulphide ore solutions. This later magnetite is also usually bluish in color and in a few polished sections carries plates of ilmenite.

The pyrrhotite is present in large grains and is the predominant sulphide of the ore. Many of the grains have a distinct hexagonal outline. As the pyrrhotite replaces the primary rock minerals a blue-green hornblende and brown biotite precede it.

The pentlandite is usually present either as crystals in the pyrrhotite or as veinlets cutting it. As a rule the mineral can be shown to be definitely later than the main mass of the pyrrhotite. Usually pentlandite can be detected only by use of the micro-

[17] This interesting fact was mentioned by Coleman in 1905. "The Sudbury Nickel Field," Rept. Bureau of Mines, Canada, 1905, p. 125.

scope but in some of the lower levels and particularly in the hanging side ore body the mineral is exceptionally abundant in large glistening two inch crystals. In the outcrops this mineral is in part altered to limonite. So selective is the action of the weathering solutions that pentlandite may be entirely altered before the other sulphides are perceptibly affected.

Chalmersite, or at least a mineral with similar properties, was seen in a few polished surfaces of Creighton mine ore. The mineral appears to be younger than pyrrhotite and older than chalcopyrite.

The chalcopyrite occurs as veinlets cutting the pyrrhotite and as grains in the pyrrhotite closely following the pentlandite. In many instances the chalcopyrite can be seen fingering into the pentlandite and replacing it. The chalcopyrite also occurs as sharpcut euhedral crystals in the pyrrhotite and here it appears older than the pyrrhotite immediately surrounding it. Such relations are, however, to be expected when the period of one mineral overlaps that of another.

Sphalerite [18] is developed in the chalcopyrite in minute grains. This mineral has apparently been overlooked by other investigators of the Creighton ore. In age the mineral is closely related to the chalcopyrite.

Within the pyrrhotite and apparently earlier are minute grains of arsenopyrite. A little pyrite is also to be found in the ore. In the pyrrhotite the pyrite occurs in small clean cut grains but in the pentlandite it invariably has a ragged outline.

The plan of development of the Creighton mine makes it possible to study the foot wall immediately under the ore bodies. On the 18th and 20th levels we were particularly impressed by several small fissures showing not only the sulphide minerals of the ore bodies but also the gangue minerals. These veins are small, rarely over 5 inches wide. Against the country rock the vein walls consist essentially of biotite and hornblende. The center of the veins may carry albite having 2 inch cleavage faces

[18] Tolman and Rogers do not believe pyrite and sphalerite to be magmatic minerals. We found them in the ores of all of the mines examined. C. M. Dresser also reports pyrite as a common mineral.

and also quartz, calcite and the sulphides. It seems to us a significant point in favor of a replacement origin of the ores that veins carrying the minerals which accompany the ores of the large ore bodies also cut the foot wall rocks.

The Murray Mine.—The Murray was classified by Coleman as a marginal deposit and like the Creighton, has been thought of as an example of a deposit formed by magmatic segregation. Our specimens, taken from the 7th level and representative of a single section from foot to hanging, show greenstone, quartz gabbro, quartzite, and the typical quartz norite of the nickel eruptive.

The greenstone resembles that at the Creighton and is cut by veinlets of aplite. The granitized greenstone is also well epidotized, in this respect being strikingly similar to the occurrence at Levack. The ore cuts both the greenstone and aplite and so is later. The stringers of aplite appear to be unrelated to the ore solutions but seem to be apophyses of a nearby stock of granite.[19]

Coarse quartz is locally abundant. This quartz in many respects resembles the coarse quartz from the Garson. It is suggested that it is not a secondary product due to the ore solutions, but rather is the recrystallized product of quartzite altered by contact metamorphism.

The gabbro (or rather a quartz gabbro consisting of pyroxene, labradorite, quartz, hornblende, biotite, apatite) is supposedly younger than the greenstone because of its fresh appearance as contrasted with the highly altered appearance of the greenstone. The ore in places is preferentially developed in the gabbro. The pyroxene of the rock is well uralitized; the biotite and the hornblende alter to chlorite; and the plagioclase carries a little secondary epidote. Where the sulphides occur, the rock shows the usual development of blue-green hornblende and brown biotite. In this basic rock as in many others of the district there are three varieties of amphibole developed: (1) that formed by crystallizing from the rock melt; (2) actinolite resulting from the altera-

[19] Barlow, Geol. Sur. Canada, Special Rpt. No. 961, 1907, p. 78, and C. W. Knight, "Nickel Deposits of the World," 1917, p. 180, mention granite as cutting the norite.

tion of pyroxene; (3) a blue-green hornblende intimately associated with and replaced by the sulphides.

The hanging wall norite is a typical quartz norite consisting of labradorite, a deeply pleochroic hypersthene, monoclinic pyroxene, hornblende, biotite, quartz, and apatite. Very fresh specimens of this rock may be obtained. Chlorite, calcite, titanite, serpentine, epidote, zoisite, actinolite, blue-green hornblende and the sulphides are present as secondary minerals. The actinolite replaced the pyroxenes; the calcite, zoisite, and the epidote are best developed in the plagioclase; the chlorite replaced the biotite; wherever the sulphides occur the blue-green hornblende is usually intimately related to them.

The ore minerals as seen in polished sections are magnetite, pyrrhotite, chalcopyrite, pentlandite, sphalerite, and pyrite. They exhibit the same characteristics of order and occurrence as do the opaque minerals at the Creighton mine.

Levack.—The ore deposit at the Levack is in the gneissic granite about 200–300 feet away from the norite-granite contact. (See Fig. 23.) It differs from the Creighton deposit in

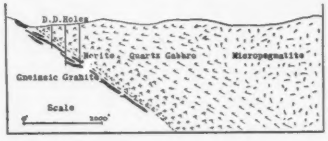


FIG. 23. Idealized section at the Levack mine. After C. B. Brackenbury (Ont. Bur. of Mines, 23rd Ann. Rep., 1914, p. 194) and our own notes.

that the ore bodies are entirely removed from the norite contact; that the ore carries much more rock in proportion to sulphide, necessitating about 33 per cent. of hand sorting; that the minerals associated indicate a lower temperature of the mineralizing solutions.

The details of the petrology of this deposit are rather complex. In a broad way granite intruded a basic rock called greenstone, and fragments of the latter rock in various stages of alter-

ation are preserved in the granite. Exposures in the open cut show excellent examples of granitized brecciated greenstone.

As mentioned above the ore bodies occur well removed from the norite contact. That the norite is younger than the granite is conclusively established.[20] Although the main ore body occurs within the gneissic granite and the granitized greenstone, disseminated sulphide is found also in the quartz norite, but it is by no means abundant enough to be regarded as ore and differs little from other similar occurrences.

The details of ore mineralization are obscured because prior to mineralization the rock had already passed through a complex history. This rock, now represented by fragments in various stages of granitization, has been termed a greenstone. Judging from the minerals now remaining the original rock was a quartz-augite-gabbro. The various steps leading to complete granitization are still fairly decipherable. Among these steps are; (1) The breakdown of the large crystals of pyroxene to form a multitude of small crystals of pyroxene, magnetite, biotite, plagioclase and hornblende (actinolite); and the breakdown of the large crystals of plagioclase into a mosaic of small crystals of plagioclase. (2) The pyroxene is gradually replaced and the hornblende and the magnetite tend to form larger grains; the plagioclase changes from labradorite to oligoclase and albite. (3) The oligoclase and albite increase in amount, although preserving the granular habit, and apatite and quartz begin to become abundant. (4) With the advent of the quartz the hornblende begins to disappear. (5) The end result is a rock consisting essentially of albite, oligoclase, hornblende, a little biotite, and with apatite and magnetite as accessories. The development of the sulphides and the associated minerals follows the above mentioned steps.

The Levack deposits carry much pyrite and this appears to have been the earliest sulphide. All of the sulphides, it may be mentioned, develop in the fragments of altered greenstone in preference to the granite. With the advent of the sulphides the

[20] "Nickel Deposits of the World," 1917, p. 163.

albite and oligoclase formed during the period of granitization of the greenstone become cloudy with chlorite, epidote, zoisite, calcite, and sericite. Even the apatite alters to epidote. In the basic rock magnetite has been largely replaced by green chlorite, epidote, and titanite. The hornblende formed during the period of granitization altered to chlorite, carbonate, quartz and epidote. The biotite of the same period changed to chlorite and rutile. Where the sulphides become abundant there is developed in addition to the hornblende and biotite such as characterize the ores of the Creighton deposit, chlorite, epidote, quartz and calcite. These minerals are all intimately related to the sulphides and can be seen replacing the other rock constituents. Late in the period of mineralization a little serpentine formed in fractures which cut the other silicates and the sulphides.

The hanging wall norite differs somewhat from that found at the Creighton mine. In the hand specimen it is lighter in color and suggests a diorite. Under the microscope it is seen to be composed of labradorite, hypersthene, micropegmatite, monoclinic pyroxene, hornblende, biotite, quartz, apatite and magnetite. Chlorite, epidote, zoisite, and sericite are the common secondary minerals.

The opaque minerals are pyrite, magnetite, pyrrhotite, pentlandite, chalcopyrite, sphalerite, and polydymite.

Pyrite is abundant in this deposit and locally exceeds the pyrrhotite in amount. The magnetite, usually in nests and clusters of euhedral crystals, is younger than the pyrite, for crystals of magnetite rest upon crystals of pyrite. Later than the magnetite is the pyrrhotite. It is of interest that a ferrous sulphide mineral should follow a ferrous oxide. Pentlandite and chalcopyrite are similar in habit and occurrence as in the other deposits. In the upper workings of the mine the pentlandite altered to a mineral determined as polydymite. The polydymite is evidently due to supergene solutions. Even though the pentlandite may be almost completely altered the pyrrhotite, chalcopyrite and sphalerite adjoining fail to show any effects of oxidizing solutions. It is entirely probable that the excellent cleavage of the pentlandite

made this mineral particularly susceptible to the action of secondary solutions.

Crean Hill.—Our specimens from this locality are few in number and represent merely the ore-bearing rock. The rock in which most of the ore occurs is a quartz diorite. The essential minerals are plagioclase feldspar (albite to labradorite), brown biotite, green hornblende and quartz. As accessorites are present magnetite, apatite, and a little micropegmatite. Titanite, sericite, calcite, epidote, chlorite, and rutile are the chief secondary minerals. All of the specimens examined show that the rock had been sheared, the biotite and the hornblende now having a ragged and frayed appearance. Included fragments, probably shale, show contact metamorphism. These fragments are now composed largely of chlorite with which are associated scapolite, apatite and tourmaline.

The sulphides appear to be later than the quartz diorite and also later than the contact metamorphism. Hornblende, biotite and chlorite accompany the sulphides. As is usual for these deposits magnetite is developed with and preceded the pyrrhotite, pentlandite, chalcopyrite, and sphalerite. The order of deposition of these minerals is the same as at the Creighton mine.

MINES UNRELATED TO THE CONTACT.

Copper Cliff.—The deposit at Copper Cliff occurs as a cylindrical pipe-like shoot in a fine-grained quartz diorite that very much resembles the quartz diorite found at Crean Hill. The diorite is an isolated mass that has no apparent connection with the main nickel eruptive.[21] Under the microscope the rock is seen to be composed of plagioclase feldspar, brown biotite, hornblende, quartz, apatite, and magnetite. The shreddy appearance of the biotite and hornblende is indicative of shearing. The early or primary magnetite has altered to titanite. The sulphides are clearly later than the silicate minerals enumerated above. Associated with the sulphides are the blue-green hornblende and brown biotite that have been mentioned as accompanying the

[21] A. P. Coleman, "The Nickel Industry," 1913, p. 69, believes the diorite to be an offshoot from the main nickel eruptive.

marginal deposits. In this ore body there appears to be a slight falling off in the amount of magnetite as compared with the Creighton, but sphalerite and arsenopyrite seem to be more abundant.

Stobie Mine.—The deposit at the Stobie mine occurs in a fine-grained quartz diorite dike that cuts the schistose greywackes and quartzites of the Temiskaming series. This dike is not connected on the surface with the Frood offset deposit which lies about 400 yards to the west, and has no apparent connection with the main nickel eruptive which is about 1½ miles to the north. The typical quartz diorite, as represented by our specimens, is a dark-colored rock of medium grain, is slightly sheared, and carries as its essential minerals oligoclase to andesine feldspar, hornblende, brown biotite, and quartz. As accessories are present magnetite, apatite, and albite-quartz micropegmatite. In contact with the diorite are greenstone schists. Due to contact metamorphism, perhaps by the quartz diorite, the schists are now composed largely of albite, quartz, biotite, hornblende, chlorite, garnet, apatite, and magnetite.

As the various rocks become impregnated with the sulphides a margin of blue-green hornblende and brown biotite replaced the rock minerals ahead of the ore minerals thus recalling the rock alteration at the Creighton mine. Near the sulphides the biotite and hornblende are slightly replaced by chlorite. Locally a little epidote and quartz are developed.

The Frood Mine.—This deposit, to the west of the Stobie, is frequently spoken of as its extension. The ore consists only to a minor degree of massive sulphide, but is largely a dissemination of eyes of sulphide in basic rock. The mine is low grade but a great tonnage, 45 million tons, has been developed by diamond drilling. The ore, in the main, occurs spotted through an intrusive dike-like body of quartz diorite which cuts schistose greywackes and quartzites. Our study of the ore bearing rock is essentially in agreement with Howe,[22] who determined the rock to be a diorite thus differing from Coleman [23] who regarded this

[22] Econ. Geology, Vol. 9, Sept., 1914, p. 508.

[23] "The Nickel Industry," Dept. Mines, Canada, 1913.

rock as a norite. Nearby is an intrusive of gabbro which has been determined as younger[24] than the diorite. The gabbro as well as the diorite and the Temiskaming sediments carry ore. The gabbro appears to have been well brecciated before the ore solutions entered for the ore cements fragments of the gabbro. In the diorite, on the other hand, the ore occurs as blebs rarely over a half inch in section. These blebs at once recall the grains of sulphide in certain phases of the main nickel eruptive, and in the hand specimen the ore suggests that sulphides and silicates were formed contemporaneously. There are however abundant specimens which show that the sulphides cut the diorite.

Thin sections of the ore-bearing igneous rock show this to be a sheared quartz diorite. As essential minerals are present green hornblende, labradorite, quartz, with magnetite and apatite as accessorites. As secondary minerals there are present actinolite, quartz, biotite, blue-green hornblende, chlorite, rutile, titanite, ankerite, sericite, and the opaque minerals magnetite, pyrrhotite, pentlandite, chalcopyrite, and sphalerite. Hypersthene was carefully looked for but neither this mineral nor its alteration products could be detected.

The slightly mineralized quartz diorite differs from the well mineralized not only in the habit of the sulphide grains but also in the amount of secondary hornblende developed. This hornblende is undoubtedly related to the presence of ore. It in turn is replaced by the sulphides. A chance section might easily lead to the conclusion that the hornblende and the sulphides crystallized simultaneously. This is especially true of the rock that carries spots of sulphide. In the heavily mineralized rock the sulphides replace the silicate minerals and tongues and veins of sulphide dart and cut through the rock in criss-cross patterns. In the more massive ore chlorite, actinolite, quartz, ankerite, and albite are abundant, the sulphides being even later than the carbonate. Sections made from the pyrrhotite-rich specimens show the development of the blue-green hornblende, brown biotite, and replacing sulphides in a striking way. Rather large patches may

[24] "Nickel Deposits of the World," C. W. Knight, 1917, p. 187.

be composed entirely of blue-green hornblende and pyrrhotite, with the evidence clear that the pyrrhotite replaced the hornblende.

Magnetite occurs in two generations. The early variety, in anhedral, somewhat skeletal grains in the biotite, has evidently been resorbed and also altered, in a large measure, to titanite; the late variety either euhedral or of irregular outline is frequently embedded in the pyrrhotite. This relation of the magnetite is common for the entire district.

In many of the thin sections the plagioclase feldspar is still fresh, showing only rarely an incipient alteration to sericite. Where altered the usual change is for the large crystals of feldspar to break down into a mosaic [25] of smaller grains. This tendency for the feldspar to increase the surface area for a given volume of material is similar to the development of granular quartz, flake biotite, and actinolite. These changes may not have anything to do with the mineralizing solutions but may be an expression of the attempt of the rock minerals to adjust themselves to the shearing strains which affected the rock shortly after its consolidation. The ores in all cases are later than this crystal breakdown.

The Worthington Mine.—The Worthington is a typical offset deposit. The ore bodies are about 3 miles from the main nickel eruptive. The ore is largely confined to a shattered dike-like mass of quartz diorite which has generally been called norite.[26] Within the quartz diorite are numerous rounded fragments of actinolitic rock. Our thin sections of typical ore show the quartz diorite to be composed of oligoclase and andesine feldspar, hornblende, biotite, quartz, and a little magnetite. The feldspar altered to zoisite, epidote, and chlorite and is also recrystallized to a multitude of fragmentary crystals. The hornblende altered to actinolite and serpentine. There are found in this rock three varieties of amphibole—the original primary hornblende that crystallized with the other primary rock minerals, actinolite

[25] A similar change has been described for the Engels deposit by Graton & McLaughlin. ECON. GEOLOGY, Vol. 14, 1918.

[26] A. P. Coleman, "The Nickel Industry," 1913, p. 76. C. W. Knight, "Nickel Deposits of the World," calls the rock a diorite.

which replaces this hornblende, and a blue-green hornblende that is intimately related to the ore minerals. Biotite, present as ordinary crystals and as flakes, altered to chlorite. A little sericite is also developed. The association of blue-green hornblende, brown biotite and quartz with the sulphides as well as the development of chlorite and serpentine are marked features of this deposit.

The polished specimens of the Worthington ores offer a slight variation from those of the Creighton, Murray, and Levack deposits. In addition to the usual pyrrhotite, pentlandite, chalcopyrite, and magnetite, there are also found in easily visible grains, galena, sphalerite, pyrite, gersdorffite, arsenopyrite, marcasite, and an unknown nickel arsenide of pink color resembling niccolite but decidedly softer.

The sphalerite, in most of the other deposits, is found sparingly in minute microscopic crystals. Here it is found in crystals and veins easily seen by the naked eye. Some specimens consist of sphalerite and chalcopyrite intimately intergrown. Both sphalerite and galena are associated with the pyrrhotite in a way to show that they belong to the main period of mineralization. Gersdorfite and arsenopyrite occur in large crystals enclosing the pyrrhotite, pentlandite and chalcopyrite. The unknown nickel mineral with the color of niccolite has a hardness of 4, and a fair cleavage that seems pinacoidal. The mineral gives a good nickel and a good arsenic test but does not react for sulphur. Etching tests rule out maucherite, chloanthite, and rammelsbergite. Pentlandite occurs in extra large crystals, some of them measuring 2 inches in section. Marcasite is confined to a vein in a shatter zone. It does not appear to belong to the main period of mineralization. It usually rests upon quartz and is coated with calcite.

COMPARISON OF MARGINAL WITH OFFSET DEPOSITS.

The first striking difference between the marginal and the offset deposits is that the former are found at the contact of the main nickel eruptive and the older underlying rocks; the latter

are intimately associated with dike or stock-like bodies having the mineral composition of a quartz diorite. But these quartz diorites are not confined to the offset deposits, for in the Creighton mine, the typical marginal deposit, there has been observed not only a body of quartz diorite [27] that cuts the norite and is itself mineralized but also a dike of augite diorite that also cuts the norite and is heavily mineralized.

As regards occurrence these types of deposits have much in common. In each, the ore replaces one or more varieties of rock that was distinctly brecciated before being affected by the ore solutions.

In general rock replacement was much the same in each type of deposit. Biotite, hornblende, albite, quartz, epidote, chlorite, and carbonates are the important gangue minerals. The black replacement borders due to the ferromagnesian minerals form a striking feature of the rock alteration. The development of epidote, zoisite, calcite, chlorite, and titanite so well shown at Levack is also evidence of the action of solutions. There appears to be more of the mineral chlorite away from the contact.

Between the typical marginal deposits and the typical offset deposits upon the southern limb of the nickel eruptive there are distinct differences in the relative amounts of sulphides and arsenide minerals deposited. Thus pyrite, sphalerite, and galena increase in amount going away from the contact, whereas the amount of magnetite decreases. In the case of the gangue minerals there are also slight differences. Siderite, quartz, chlorite, and serpentine become distinctly more abundant away from the contact.

In spite of the minor local differences the ore minerals are decidedly alike and the wall rock alterations have much in common. In a study of the ores, one becomes convinced that the differences are merely a matter of degree and that the ores regardless of the types of deposit in which they now occur all had a common source and origin.

The similarity of these deposits is shown by Table II.

[27] Staff of the International Nickel Company, *Can. Inst. Min. and Met.*, March, 1920.

TABLE II.

PARAGENESIS AND OCCURRENCE OF MINERALS.

CHIEF TYPES OF COUNTRY ROCK.	Type of Deposit.								
	Marginal.					Offset.			
	Creighton.	Murray.	Garson.	Crean Hill.	Levack.	Frood.	Stobie.	Copper Cliff.	Worthington.
Greenstone	×	×	×	×	×	×	×	×	×
Schist		×		×		×	×	×	×
Quartzite		×	×			×		×	×
Granite	×	×			×			×	
Quartz Norite	×	×			×				
Quartz Gabbro		×			×				
Quartz Diorite	×		×	×		×	×	×	×
Minerals of the Ore Forming Period (in approximate order of formation).									
Clinochlorite						×			
Hornblende	×	×	×	×	×	×	×	×	×
Biotite	×	×	×	×	×	×	×	×	×
Albite	×	×	×	×	×	×	×	×	×
Quartz	×	×	×	×	×	×	×	×	×
Chlorite	×				×	×	×	×	×
Epidote	×		×		×		×	×	×
Zoisite	×					×	×	×	×
Sericite	×				×	×	×	×	×
Siderite			×			×			
Calcite	×				×		×	×	×
Pyrite	×	×	×	×	×	×	×	×	×
Arsenopyrite	×	×	×	×	×	×	×	×	×
Magnetite	×	×	×	×	×	×	×	×	×
Pyrrhotite	×	×	×	×	×	×	×	×	×
Pentlandite	×	×	×	×	×	×	×	×	×
Chalcopyrite	×	×	×	×	×	×	×	×	×
Sphalerite	×	×	×	×	×	×	×	×	×
Galena	×	×	×	×	×	×	×	×	×
Gersdorffite									×
Nickel Arsenide									×
Post Ore Minerals.									
Chlorite	×		×		×				×
Serpentine	×		×		×	×	×	×	×
Quartz	×	×	×	×	×	×	×	×	×
Marcasite									×
Calcite									×
Minerals Due to Weathering.									
Polydymite	×	×	×	×	×	×	×	×	×
Limonite	×	×	×	×	×	×	×	×	×
Calcite			×		×				×

GENESIS OF THE DEPOSITS.

The genesis of the Sudbury deposits has long been a bone of contention with geologists and mining men. From the remarkable similarity of the primary mineralization as shown in Table II., it seems evident that the offset and marginal deposits were formed by the same agencies under similar conditions in the same metallogenetic epoch. Any theory of genesis must explain both types of deposits.

The following theories of origin have been advanced.

(1) Magmatic Differentiation.[28]
(2) Formation by Hydrothermal agencies.[29]
(3) Modified Magmatic Theory.[30]
(4) Sulphide Injection.[31]

A detailed discussion of these various theories is beyond the scope of this paper, especially since excellent summaries can be found in the papers by Tolman and Rogers and by Bateman, and in the report of the Ontario Nickel Commission by C. W. Knight. The papers by A. P. Coleman contain many of the details of ore occurrence and are most valuable reference works.

The facts of ore occurrence at Sudbury and our own interpretation of some of them are as follows:

1. The chief intrusive mass of the district is the nickel eruptive. This igneous mass shows a striking differentiation from

[28] Adams, F. D., *Canadian Min. Rev.*, 1894.
Bell, R., *Bull. Geol. Soc. Amer.*, Vol. 2, 1890.
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[29] Dickson, C. W., *Trans. A. I. M. E.*, Vol. 34, 1903.
Knight, C. W. and Campbell, M., ECON. GEOL., Vol. 2, 1907.
Knight, C. W., "Nickel Deposits of the World," Canada, 1917.
Beck, R., "Lehre von der Erzlagerstatten."

[30] Tolman and Rogers, Leland Stan. Jr. Pub. Uni. Ser., 1916.

[31] Howe, E., ECON. GEOL., Sept., 1914.
Bateman, A. M., ECON. GEOL., 1917.
Lindgren, W., ECON. GEOL., 1920.
Staff of the International Nickel Company, *Can. Min. Inst.*, 1920.

typical hypersthene quartz norite at the lower contact to granite at the upper contact.

2. The magma before differentiation seems to have had the composition of a quartz diorite.

3. Throughout the differentiated igneous body there are small blebs of sulphide. These blebs of sulphide are usually more abundant in the quartz gabbro and quartz norite phases than in the granite phases. This basic rock with its spots of sulphide is, however, in no sense to be regarded as ore, for the sulphides constitute less than one half of one per cent. of the rock. At the Creighton mine such a zone of spotted quartz norite, six hundred yards wide and three quarters of a mile long, occurs several hundred feet distant from the contact. Here again, this zone is in no sense to be regarded as ore.

4. The lower contact of the norite is frequently finer grained than is the rock 300 feet away from the contact thus showing that the intruded norite was chilled.

5. The norite is shattered and sheared. At the Creighton mine veins of sulphide with chlorite, quartz, and carbonate cut the norite.

6. The ore bodies are found either at the lower contact of the nickel eruptive or at variable distances up to 3 miles in the adjacent underlying rocks, associated with intrusives of quartz diorite.

7. Throughout the differentiated igneous body there are local streaks of pegmatite, some of which show tourmaline and all of which are marked by abundant apatite, quartz, and usually a little sulphide.

8. The offset deposits such as the Frood, Stobie, and Worthington are associated with quartz diorite and not with norite. Pyroxenite [32] or some other very basic rock has not been found in association with an ore body.

9. At the Levack mine layers of ore are separated by layers

[32] Such associations have been described at other localities where the ores are believed to be magmatic differentiates. See descriptions by Goodchild, *Trans. Inst. Min. and Met.*, London, 1917; A. Knopf, ECON. GEOLOGY, Vol. 9, 1913; Dracut, Mass. Unpublished paper by E. Fairbanks.

of granite with the ore bodies beginning at some distance below the norite contact.

10. In all cases, whether dealing with a marginal or an offset deposit or even a narrow vein in the norite, there is evidence of shattering that opened the way for the ore solutions, and also evidence that these solutions replaced rock material.

11. Replacement of rock with the formation of solid sulphide is on no larger scale than in other mines of solid sulphide as the United Verde, Ducktown, and Rio Tinto.

12. In each mine of the Sudbury district the rock alteration associated with the ore can be seen when once the type of alteration is recognized.

13. The peculiar type of alteration is seen with difficulty in hand specimens of ore in greenstone, diorite, or norite. In the Creighton mine [33] this type of rock alteration is most easily seen where the ore is replacing granite.

14. The rock alteration which accompanies the sulphide is characterized by the development of blue-green hornblende (a variety of amphibole having the properties of actinolite), brown biotite, quartz, and albite. Epidote, zoisite, sericite, and carbonates are developed to a lesser degree except in the Levack mine where epidote is an abundant rock alteration mineral.

15. Before a marginal deposit like the Creighton was formed the norite had consolidated a goodly distance from its lower contact, as is shown by the dikes of quartz diorite and augite diorite which cut the norite and are themselves in places thoroughly shattered and replaced by sulphide in the zone of the main Creighton ore body.

16. Since the norite had chilled inward from its lower contact a sufficient distance to permit this marginal zone to be cut by dikes unlike the norite in composition, and since the ore occurs at the base of this chilled zone or well below it, it becomes increasingly clear that even such a typical marginal deposit as the Creighton can not have been formed by any process that calls for gravitative differentiation in situ.

[33] See report by the staff of the Int. Nickel Co., *Can. Inst. Min.*, 1920.

17. Brecciation and rock replacement are two striking features of the Sudbury ore deposits, hence a straight sulphide injection of the ores can not be appealed to as the process best explaining the origin of these ore bodies.

18. Pyroxene and olivine in association with the sulphides are conspicuous by their absence. Blue-green hornblende, biotite, albite, and quartz are the chief gangue minerals.

19. The sulphide minerals replace silicates. The silicates immediately undergoing replacement are those listed as gangue minerals and which have replaced the primary rock minerals.

20. The ore minerals [34] whether in a marginal or an offset deposit always show the same general order of formation,—pyrite, magnetite, pyrrhotite, pentlandite, chalcopyrite, sphalerite, galena. These minerals overlap each other in time of formation and also vary in abundance from place to place.

21. No ore body has been found within the nickel eruptive.

These are the facts of occurrence as brought out by our study. Any theory of origin must explain these facts. To us it seems that these facts all indicate a deep-seated source for the ore solutions; perhaps the same magmatic reservoir which furnished the magma of the nickel eruptive also furnished the ore. The peculiar gangue minerals indicate a high temperature type of deposit. We are forced, therefore, to conclude that the ores were derived from a deep-seated source and represent a high temperature type of ore deposit associated with basic rather than the usual acidic type of intrusive. The Sudbury ore deposits are then to be classed among the pneumatolytic deposits.

One question commonly raised by those favoring the magmatic theory of origin is why, if shattering preceded ore, are the ores found at the base of the nickel eruptive and not within in the main body of this intrusive which in places is cut by faults.

[34] A suite of specimens from Insizwa, South Africa, collected by Prof. R. A. Daly, were studied by means of polished surfaces by Mr. A. W. Pinger, a graduate student at Harvard University. Mr. Pinger reported that the chief sulphides in their order of deposition are pyrrhotite, pentlandite, chalmersite, chalcopyrite, and sphalerite. This is the same order of deposition as at Sudbury and not the reverse as reported by Goodchild. Chalmersite is vastly more abundant in the Insizwa deposit than at Sudbury.

The answer that suggests itself is that along the contact of the nickel eruptive and the underlying rocks there was in places, due to the intrusion of the nickel eruptive, a zone of fracturing which the ore solutions could easily search out. The solutions would then be able to choose between a clean cut break in the norite and a shattered region along the contact. As a result the shattered region (a zone of great permeability) underwent extensive replacement; the clean cut breaks in the norite, on the other hand, (pathways of limited permeability) tapped but a small part of the ore solutions and so carry narrow veinlets of the sulphides.

The occurrence of these deposits near an intrusive is not unlike that commonly met with in contact deposits. The mineralization of such deposits as the Worthington and Ross, ore replacing a shattered dike-like intrusive, is a common feature for many other ore deposits that are considered to be replacement deposits.

Another great difficulty in accepting the pneumatolytic hypothesis seems to be the absence of the usual hydrothermal minerals, as sericite, which are familiar to students of pyritic deposits. Our study convinces us that there is plenty of rock alteration of an unusual type. It may well be that this unusual type of alteration is due: (1) the ore solutions entered warm rocks, warm because the period of ore deposition followed close upon the period of intrusion; (2) the temperature of deposition was high. Thus causing hornblende and biotite to form instead of chlorite and sericite.

BEARING OF GENESIS UPON EXPLORATION.

By the man interested in the existence of new ore the question may well be raised as to the value of lengthy and detailed discussions of occurrence and speculations regarding origin. It must, however, be evident to all that if once the facts of occurrence are established for the known ore bodies then the policy of mining will receive guidance and the exploration for new ore may be conducted with the minimum of outlay.

In the early days the observations by Barlow and his associates that the ore bodies were more or less localized at the lower contact of the nickel eruptive certainly gave the best possible hint as

to where to prospect. Later Coleman [35] narrowed the field somewhat by noting that certain large ore bodies were found in bays at the base of the norite. There are, however, some ore bodies that are not found at such embayments, as the Falconbridge and the mines from the Murray to the Sheppard.

Our study has not been general enough to warrant laying down any additional rules for prospecting. If, however, our observations regarding mineralization are right then it seems as though the question of persistence of ore with depth may well be answered. With magmatic segregation only hollows and bays were favorable for ore and any ore body was merely a chance pod that might come to end suddenly at any time. There would, moreover, be no good reason why another lens of ore should be found in depth to take the place of the lens which was bottomed.

Assuming that the theory upholding a high temperature replacement origin for the ores is right and that the ore solutions had a deep-seated source and rose along zones and belts of shattering there is every reason, then, to believe that the ores will persist in depth. What the limits in depth will be cannot be stated, but the widening experience of mines working in primary ores is that this may well be several thousand feet. All of the vagaries of any primary hypogene ore deposit are to be looked for. Among such vagaries are the occurrence of shoots of ore; shoots of ore that do not outcrop; the confinement of the ore to certain structural features such as shear zones; the association of ore with brecciated dikes; a narrowing of a given shoot with its end seemingly in sight only to have the shoot widen in depth; variations of grade with depth but on the whole no decrease; one ore shoot followed by another in depth. Encouragement is thus given to the miner to develop in depth and to keep such development well ahead of extraction. As the structural details are worked out it is also possible that new and large ore bodies will be discovered.

[35] "The Sudbury Nickel Field," 1905.

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EDITORIAL

SCIENCE AND DOGMA.

ALTHOUGH dogmatism, or the formal assertion that certain concepts or principles are to be accepted as truth, is commonly associated in our minds with theology, the dogmatic spirit is by no means absent from other fields of thought. It appears to be a common human weakness to forget the insufficiency of evidence and to accept and maintain as proved what in reality is little more than conjecture or hypothesis.

Scientific men, notwithstanding the austerity of their professions as regards the single-minded reliance upon evidence as the only safe guide to truth, are not wholly unswayed by the will to believe and the desire to have others believe as they do. Even in physics, a branch of science in which progress rests largely on experimental and mathematical demonstration, the existence of the ether has sometimes been accepted with a confidence so implicit as to leave a doubter in little better state scientifically than one who, theologically, has committed the unpardonable sin against the Holy Ghost. Geology, notwithstanding the wonderful additions to knowledge made in that science and the substantial foundation upon which those advances rest, is a less exact science than physics. The geologist deals with the results of processes that have been in operation under conditions that he can not fully reproduce in the laboratory and which have acted through periods of time so vast as to be beyond his comprehension. Many of these processes he can never hope to see in action. His explanation, for example, of the formation of a gold-bearing quartz vein must inevitably involve an imaginative projection from the realm of the known into the shadowy realm of the unknown. The explanation may accord with such evidence as is available and may appear eminently reasonable but definite proof is unattainable and may always remain so.

In these days of a recrudescence of dogmatic medieval theology it is appropriate that scientific men subject their own views to candid examination and of this wholesome discipline geologists, and particularly economic geologists, perhaps stand especially in need.

As we all know, opinions on the origin of ore deposits have varied widely from period to period. There has never been unanimity but from time to time, one view or another, because of the brilliant advocacy of one or more leaders, has been in the ascendent. Although the analogy may seem superficial or frivolous to some, there is reason to believe that there are prevailing fashions in opinion as there are in clothes or manners. We can remember when the supposition that the metals of ore deposits were leached from the adjacent wall rocks by cold underground water held sway. At another period the dominant view was that meteoric water, after descent to great depth and passage through many kinds of rock, with some increase in its temperature, rose through trunk channels and deposited its gathered load of metals in the ore deposits as we find them. At other periods, the significant association of many ore deposits with igneous rocks has received particular recognition and has been interpreted in various ways. Some have seen in this association chiefly a source of heat for increasing the chemical activity of circulating meteoric water. Others have considered that the water and its contained ore constituents have been expelled from the crystallizing magma and have pointed to hot springs as the places where these solutions, after depositing most of their lode of dissolved material, issue at the surface. Still others have regarded some or most ore deposits as differentiates from rock magma and as intrusive bodies injected in molten condition in the same manner as ordinary dikes. Between these baldly stated and extreme views various intermediate opinions have been held by many students of ore deposits, as would naturally be expected from the fact that no definite distinction is possible between a cold aqueous solution, a hot aqueous solution, and a molten magma. Moreover, at the temperature and pressure at which many ore deposits

have supposedly been formed, the distinction between matter in the liquid and gaseous state is equally indefinite.

At the present time, the view that most epigenetic ore deposits were derived from the slow cooling and crystallization of rock magmas is undoubtedly the most prevalent one, although those who hold this general opinion differ as to the concentration of the metal-bearing differentiate or solution given off from the magma and as to the mode of injection and deposition of the ore. Whole-hearted adherents of this view hold that for such epigenetic deposits as show no obvious connection with intrusive igneous rocks it is more reasonable to suppose that there is an unexposed body of intrusive rock in their vicinity than to account for them by deposition from solutions of underground meteoric water. They explain in this way the lead-zinc deposits of the Mississippi Valley and of Upper Silesia and the Alps in Europe.

No one who reviews the literature of ore deposits, particularly with a view to teaching, can fail to note, with something like consternation, the diversity of opinion as to their origin. There is scarcely an epigenetic deposit concerning which competent investigators do not hold different views of genesis. Obviously, under such circumstances, there is a temptation to the teacher to avoid the discussion of these divergent conclusions and to present to his students, with some assurance, the particular view that he favors. There is an instinctive feeling that the minds under his instruction may become confused or discouraged unless his statements with reference to ore genesis can be presented with some air of confidence and certitude. In other words, there is a tendency to become dogmatic and this tendency, far from being confined to the class room, finds exemplification in text-books and even in works that set forth the results of research. Probably most of us have an underlying feeling of regret that our knowledge of how ores are deposited is not more definite and are unconsciously moved thereby to express our opinions with rather more confidence than the facts warrant.

The present editorial is an attempt to direct the attention of writers on ore deposits to this condition and is a plea for the

frank admission of ignorance where the facts do not justify positive assertions. An impartial retrospect over the history of opinion on ore genesis suggests that no one of the familiar or current hypotheses can account for all ore deposits and that no one of them is a complete or final explanation. Would it not be well to face this situation with candor and to impress upon the student the desirability of examining each deposit with all hypotheses in mind but with prior commitment to none? Are there not possibilities in colloidal chemistry, in diffusion, and perhaps along other lines, that have not yet been adequately considered as factors in the genesis of ores?

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DISCUSSION AND INFORMAL COMMUNICATIONS

PRIMARY RELATIONSHIPS AND UNUSUAL CHALCOPYRITE IN COPPER DEPOSITS AT PARRY SOUND, ONTARIO.

Sir: The writer has recently described the occurrence of chalmersite (cubanite) at Parry Sound.[1] Further studies of these ores have revealed textures and paragenetic relationships which are believed to be characteristic of high temperature deposits. The copper deposits lie near the town of Parry Sound on the east shore of Georgian Bay, Lake Huron. Although the deposits were discovered in 1894 they have not been put on a productive basis to date. The specimens examined are mainly from the Wilcox and McGown mines. The ores of the Wilcox mine are garnet, biotite schists with masses and disseminations of sulphides and those of the McGown mine are mainly quartz-bornite aggregates which also contain garnet, biotite, etc. Thin sections show that the rocks found in the mines are, with one exception, metamorphosed and for the most part of a basic type. There is abundant evidence that the ore minerals were introduced after the metamorphism of the country rocks, as they fill fractures cutting the rock minerals and follow the schistosity of the rock and the cleavage of biotite.

The ore minerals, and closely associated metallic minerals are: pyrite, pyrrhotite, chalcopyrite, cubanite, bornite, magnetite, hematite, sphalerite, chalcocite, covellite, malachite, and hisingerite. The McGown ore is dominantly bornite with secondary

[1] Schwartz, G. M., "Chalmersite at Fierro, N. M., with a Note on its Occurrence at Parry Sound, Ontario," ECON. GEOL., Vol. 18, pp. 270–277, 1923.

chalcocite and malachite. The Wilcox ore consists mainly of pyrite, chalcopyrite, pyrrhotite, cubanite, sphalerite, and hisingerite.

Chalcopyrite is the most important ore mineral in the Wilcox ore in which it occurs as masses, disseminations and veinlets. It is, as a rule, distinctly later than pyrite and pyrrhotite, but in rare cases is earlier than pyrrhotite.

Much of the chalcopyrite shows an unusual structure which has not been observed by the writer in chalcopyrite from other districts. These masses of chalcopyrite show a distinct parting which resembles cleavage, but obviously is not, as it shows equally well in four planes and chalcopyrite has only two poorly developed cleavages. A surface parallel to one of the partings shows three intersecting lines forming nearly equilateral triangles (Fig. 24 *a*). Examination of polished surfaces shows that this

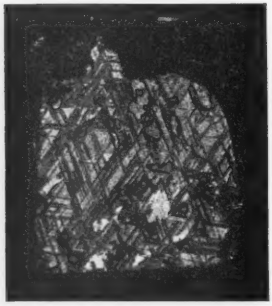

FIG. 24 *a*.

FIG. 24 *b*.

FIG. 24 *a*. Photograph of a ground surface of chalcopyrite showing three directions of parting or twinning. A fourth lies in the plane of the picture. Note the remnants of pyrite (*P*) which have been outlined. Natural size. *b*. Chalcopyrite (*Cp*) showing parting with replacement by bornite (*B*) along fractures and parting. The bornite occurs mainly as grains rather than as definite vein fillings or masses. This is probably due to the porosity of this chalcopyrite. Mag. × 65.

chalcopyrite is in all cases filled with residual, rounded grains of

pyrite (Fig. 24 *a*). Chalcopyrite masses occurring with hisingerite practically always show this structure, but it is also found with other associations. Fig. 24 *b* shows a similar structure with bornite, presumably supergene, replacing the chalcopyrite along the parting. In one specimen pyrrhotite was found along two directions of the parting. The parting formed an easy place for the access of solutions and hisingerite is commonly found following it.

The cause of this structure is perplexing. The general nature of its appearance suggests twinning. The fact that chalcopyrite is tetrahedral accounts for the four directions of the parting or striations. It is suggested that conditions prevailing during crystallization in the high temperature zone may be responsible for the development of the structure.

In addition to the primary occurrence described above chalcopyrite is also found along the cleavage of bornite in the McGown mine where it is apparently supergene.

Cubanite[2] was found in two chalcopyrite specimens from the Wilcox mine, which also contain pyrrhotite, magnetite, and sphalerite. Cubanite and chalcopyrite occur as intergrowths of laths of the two minerals with sharp contacts. The laths of cubanite may end abruptly in the chalcopyrite and in all cases cut off sharply at the contact with pyrrhotite, indicating a somewhat later crystallization for the latter mineral. It seems apparent that the chalcopyrite and cubanite are contemporaneous.

Pyrite occurs as corroded residual grains in chalcopyrite and more rarely as large grains embedded in hisingerite. It is obviously the earliest of the sulphides.

Pyrrhotite is a common, though not abundant, mineral and is closely associated with chalcopyrite in which it occurs as grains and patches clearly of earlier formation but in some specimens the pyrrhotite is later than chalcopyrite. The normal relation of pyrrhotite to chalcopyrite according to several investigators is—

[2] See Merwin, Lombard, and Allen, *American Mineralogist*, Vol. 8, pp. 135–38, 1923.

pyrrhotite earlier and replaced by chalcopyrite. However, pyrrhotite may be later than chalcopyrite as recently shown by the writer.[3]

Sphalerite is not abundant in the Parry Sound ores but was found in relations that indicate that it formed both before and after chalcopyrite but the later formation seems to be the rule.

Bornite occurs chiefly in the McGown mine where it is associated with magnetite and is believed to be hypogene for the following reasons: (1) There is an absence of residual grains of any earlier mineral. (2) It is associated with magnetite. (3) Chalcocite is only sparingly developed. (4) There is a lack of katamorphic alteration of the country rock.

Magnetite occurs as a rock mineral and as an ore mineral in this district, especially in the McGown mine. It is apparently the first ore mineral to crystallize, as it is usually granular and in some cases forms euhedral crystals in chalcopyrite.

Chalcocite, covellite, and malachite occur only as supergene minerals.

Hisingerite is an unusual mineral found in considerable amounts in the Wilcox mine where it forms a matrix for masses of pyrite and chalcopyrite. It also fills parting planes in chalcopyrite and veinlets in pyrite. It is apparently an alteration product of hypersthene and is thought to have been formed by the solutions which introduced the ore deposits.

A study of the Parry Sound deposits shows that there is as definite an order of paragenesis of the various minerals as in other types of deposits. The order normally is; magnetite, pyrite, pyrrhotite, chalcopyrite and cubanite, sphalerite; but, as noted above, pyrrhotite may be later than chalcopyrite and sphalerite earlier thus changing the order somewhat. It is believed that the order as given is more or less characteristic of deep zone copper deposits and that the occasional reversals of order indicate a very close association of the minerals in conditions and time of deposition. This reversal of order is doubtless a characteristic of high temperature deposits.

[3] *Op. cit.*, page 275.

A comparison of the Parry Sound deep zone deposits with the contact metamorphic deposits of Fierro, New Mexico, shows that they have many features in common, especially in their mineral associations and textures.

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NOTES ON MINERAGRAPHIC TECHNIQUE.

Sir: A number of articles have appeared in ECONOMIC GEOLOGY calling attention to the variation in microchemical tests afforded by the same mineral. I have especially in mind the article by H. C. Boydell, "Some Etching Tests on Pyrrhotite."[1] Schneiderhöhn[2] has studied these "secondary effects" and no doubt has found the explanation of the variations for at least a number of cases. It may be worth while to quote from Schneiderhöhn's article as I have found that the original is not readily accessible everywhere.

A difficulty which influences the diagnostic influence of many etching fluids unfavorably, consists in the following: All sulphide ores and many metallic oxides are, like metals, first-class electric conductors. Thus, if I surround two different ores which are in connection with each other, as is usually the case with massive ore materials, with an electrolyte there results from the potential difference of the two ores, an electric current by means of which the ore with the greater solution tension is dissolved. Now the ordinary etching materials are all electrolytes and the potential difference between the sulphide ores attains in individual cases the order of those between the metals. Therefore there takes place an intense dissolving action, often even by a very short immersion in an etch solution, which alone and of its own accord produces absolutely no corrosive effect on the ore mineral encountered.

A few experiments made by the writer on analyzed manganese ores appeared to require an explanation of this nature.

The examination of polished sections with polarized light pos-

[1] ECON. GEOL., Vol. 17, No. 6, Sept., 1922.

[2] Hans Schneiderhöhn, "Die Mikroskopische Untersuchung Undurchsichtiger Mineralien und Erze in Auffallenden Licht und Ihre Bedeutung für Mineralogie und Lagerstattenkunde" *Neues Jahrbuch*, Band 43, May, 1920.

sesses considerable diagnostic value although its limitation with reference to opaque minerals is well known from the work of Dr. Wright.[3] In the case of minerals which resemble very closely certain opaque minerals, but which permit the transmission of light in very thin fragments, study with polarized light will serve to distinguish the semi-transparent from the opaque ores. A good example of the application of this method is found in the ability to distinguish hausmannite from braunite when the two occur together in polished section. Wright does not mention this application and it is believed that its utility is commonly overlooked.

[3] F. E. Wright, "Examination of Ores and Metals in Polarized Light," *Min. and Met.*, No. 158, Feb., 1920, pp. 1–12; "Polarized Light in the Study of Ores and Metals," *Am. Philos. Soc. Proc.*, Vol. 58, No. 7, 1919, pp. 401–447.

ERNEST E. FAIRBANKS.

REVIEWS

Petroleum Resources of the World. By VALENTIN R. GARFIAS. New York: John Wiley & Sons, Inc., 1923, pp. xi + 243.

If one may descend from those cold altitudes of judicial criticism, which are generally regarded as affording the proper atmosphere for the review of a technical work, to the warmer regions of more ordinary human appreciation, it is in order to congratulate Mr Valentin R. Garfias upon his recently published "Petroleum Resources of the World," to compliment his publishers, John Wiley and Son, upon getting this long-expected book through the press, and to express appreciation to Mr. Garfias' associates, the Henry L. Doherty group for their broad-minded and liberal attitude in allowing publication.

"Petroleum Resources of the World" is not a treatise or monograph but is rather a handbook or introduction to the subject and will be of great interest and service to the practical oil man and to the student of economic and political aspects of the world oil situation. The book is most readable but much too brief. Instead of adopting the encyclopedic methods of Redwood or Engler and Hoefer, Mr. Garfias seems to have used, happily for a technical work, the methods applied with such success by Lytton Strachey in his notable biography of Queen Victoria; to have got his material together, digested it mentally and presented it in readable form rather than as a work of reference.

The various countries of the world are arranged for this work in two general groups, those with producing and those with prospective oil fields, and each nation or major political division receives a three-fold treatment. Firstly, by way of introduction to each country, comes a brief sketch of its geographic, economic, and political position. The information of this type makes up about a quarter of the text, is interesting, readable, and most serviceable but the salient facts are repeated in tabular form at the end of the book and by expanding these tables somewhat, the scenery could have been presented adequately if in a less attractive form and much space saved for the more pertinent discussion of the oil fields themselves. Secondly, the producing oil regions, if any, are described and a short critical statement regarding prospects is made. This description occupies about half of the text but it is entirely too brief to do the subject justice. Finally the petroleum legislation of the country is outlined, again all too briefly.

The book is concluded by a series of tables, most of which are repetitions of data appearing in the text, but one of which—the conversion tables for units of length, area, volume, and weight—is particularly valuable to one interested in foreign oil fields. It is a distinct pleasure to possess a table where one can lay hands on the acre equivalent of a *sitio de ganado Mayor* or a *square verst* or the barrel equivalent of a cubic meter, without the necessity for real and prolonged research.

The book, so far as one may judge from a first reading, is generally free from typographical errors though there is an occasional one such as the statement on p. 13 that "a maximum output of nearly 34,000,000 barrels a day" was reached in the Illinois fields in 1908.

The origin of the salt domes of the Gulf coastal plain is referred to the "power of crystallization," though the author ascribes the origin of the Roumanian salt domes to mountain building crustal movements.

The reviewer doubts whether the author is justified in a general description of the Dos Bocas-Alamo anticline or ridge of Mexico in referring to the shales overlying the Tamasopo limestones as "baked shales rendered porous by the effect of igneous intrusion." There may be baked shales overlying the Tamasopo limestone where productive on this structure but certainly they are exceptional occurrences and it is doubtful whether they are to be found in five per cent. of the area where the Tamasopo is productive and whether they have any critical importance, even in such areas. The first important production in southern Mexico was found at San Cristobal in 1907 rather than near Soledad in 1909.

The publishers announce this work as "not intended exclusively for specialists" and it is likely to be disappointing to specialists. The geologist, wishing to know about the petroleum resources of Japan, can get a birds-eye view from Garfias but if he has anything more than the most cursory interest in the subject he will fall back on Redwood or Engler and Hoefer. This is particularly true because the book contains no bibliography nor references which will assist the reader to more detailed information regarding any single area. It is to be hoped that this deficiency will be supplied in further editions.

Mr. Garfias is particularly fitted for the authorship of a work on the petroleum resources of the world. He has had broad experience as a consulting geologist. He has served the governments of the United States and Mexico in expert capacity, was professor of petroleum Engineering at Stanford University, and is at present manager for the foreign oil enterprises of the Henry L. Doherty group.

It is to be hoped that at some future date he will take advantage of his broad experience to expand the present work into one "for specialists" for after all, it is the specialist who represents ninety per cent. of the

readers of a work of this type and who make possible its profitable publication.

E. De Golyer.

Practical Experience in Electrical Prospecting. Hans Lundberg. Swedish Geological Survey, Series C, No. 319, Stockholm, 1923. Price, 2.00 kr.

As the undiscovered ore bodies which outcrop become fewer and fewer, it is natural that vigorous efforts should be made to develop methods by which those which do not outcrop or whose outcrops have been so altered as to mask their original character may be detected. A method has been developed which detects and measures the distortion produced upon the earth's magnetic field by rock bodies of different magnetic susceptibility. Other methods distinguish between various rock bodies or between ore and rock by means of their different gravitative attraction. Still other methods depend upon the electrical properties of the concealed rock. The effect upon electrical waves is studied. Electrical resistance is measured. Sulphide bodies undergoing oxidation set up earth currents whose source can be located. Or, an electrical field can be artificially established in a given region and the distortions or departures from an ideal distribution of the surfaces of equal potential, such as an ore body surrounded by rock would make, can be studied. To the latter class belongs the method of Lundberg and Nathorst, developed and applied by them in the services of the Geological Survey of Sweden and Bergsbyran, Ltd. of Stockholm. An outline of the method and accounts of the discovery of heretofore unknown ore bodies is given in the paper which is the subject of this review.

The method used is as follows: A difference in potential is applied through wire electrodes in contact with the ground along the opposite sides of a rectangular area which is to be examined. An alternating current provided by a generator is led to the electrodes. There is, of course, a fall of potential in the ground between the two parallel electrodes. If the ground is homogeneous, all points of the same potential on the surface lie along a line parallel to the electrodes. If the area contains bodies of different conductivity, the ideal parallel arrangement of the equipotential lines is not found. Certain distortions in the field are produced by the buried bodies of unequal conductivity. Different rocks have different conductivity, and bodies of certain ore minerals including pyrite, chalcopyrite, galena, specular hematite, and magnetite have a much higher conductivity than the rocks in which they occur. Thus, the geological structure of a region, and the size, shape, depth, and character of ore bodies in it produce their effects on the electrical field and such effects may be

studied and interpreted by mapping the lines of equal potential. These lines are traced by means of a telephone receiver attached by leads to two metal rods. When these rods are in contact with the ground in the area under investigation, a humming corresponding to the frequency of the generator will be heard, unless they both lie along the same equipotential curve. By holding one fixed, and moving the other about, two points along the same equipotential line can be found. In this way the line may be traced as far as desired. Other observations made are the direct measurement of potential, which makes possible the determination of the rate of fall of potential across the area, and the measurement of the intensity of the magnetic field within the area.

By reconnaissance methods, irregularities in the electrical field produced by conductors are located. These are then mapped in greater detail. Certain anomalies in the distribution of the equipotential lines and of the changes in rate of fall of potential, as indicated in potential profiles, constitute the "indications" of ore bodies.

How reliable are these "indications?" About sixty ore deposits in Sweden have been examined by this method, and enough of the "indications" have been examined by drilling or opening up to lead the author to state that it is quite clear that strong "indications" correspond in the majority of cases with ore, and weak "indications" with impregnations. In some cases, strong "indications" are shown by low-grade impregnations. Ore bodies surrounded by low-grade disseminations give the appearance of a stronger "indication," within a weaker one. Water never causes an "indication" and the degree of moisture in the soil has little disturbing effect. Buried metallic objects, such as pipe, cause disturbances in the electrical field but overhead power cables do not interfere. The depth of soil covering affects the strength of the "indication" although a depth of forty meters does not cause any considerable decrease, and theoretically even a small ore body should be observed beneath an overburden of 100 meters with the electrodes 1,000 meters apart.

The latter part of the paper is an account of the discovery by means of electrical prospecting of two ore fields, the Kristineberg and the Bjurfors, both in drift-covered areas. In the Kristineberg field, boulders of pyrite had been known for some time, but no attempts to locate the deposits were made until 1917, when there was a shortage of pyrite. Trenching near the boulders failed to find the ore bodies and electrical prospecting was tried. It resulted in an immediate success, the maps of the equipotential curves indicating the location, size, shape, and roughly the grade of the deposits, later found to be lenses of massive sulphides, chiefly pyrite and chalcopyrite, in schists.

The Bjurfors ore field was found in a similar way. Boulders of sulph-

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ide had been known for some years and unsuccessful efforts made to locate their source by sinking through the drift near them. After three years spent in electrical prospecting, the ore bodies, which were massive sulphides in schists, were found beneath 10 meters of drift and 2 kilometers (over a mile) from the nearest ore boulder.

The close correspondence between the electrical indications of ore and the ore bodies subsequently found by drilling are shown by the maps accompanying the text. The history of these two ore fields proves that in the hands of those who understand it, the method is capable of locating concealed ore bodies of certain types. If the claim of the inventors that their method can be applied successfully in spite of the variations in water content of the soil is well founded, what would seem to be a great handicap to electrical prospecting is removed.

The chief points of difference between this method and that devised by Schlumberger are as follows. Lundberg and Nathorst prefer an alternating current, while Schlumberger prefers direct current. The former trace the equipotential curves by means of a telephone receiver in the tracing circuit, while the latter uses a galvanometer for the same purpose. Lundberg and Nathorst use the "linear arrangement" of electrodes whereby the contacts with the ground are placed at intervals along the opposite sides of the rectangular area under examination. Schlumberger uses the "polar arrangement" whereby the two contacts are at points in the opposite sides of the area. The equipotential lines in the ideal field having the "linear arrangement" of electrodes are parallel straight lines, while in the ideal field having the "polar arrangement" of electrodes, they are curves eccentrically arranged about the two electrodes. The advantages claimed by Lundberg and Nathorst for the "linear arrangement" are the greater simplicity and uniformity of the ideal field and consequently the greater ease in interpreting the distortions produced by ore bodies.

T. M. Broderick.

Calumet, Michigan.

SOCIETY OF ECONOMIC GEOLOGISTS

President Kemp has appointed the following as the Executive Committee of which he is Chairman:

J. Volney Lewis,	E. DeGolyer,
S. H. Ball,	R. A. F. Penrose, Jr.,
Alan M. Bateman,	J. E. Spurr.

The Committee to arrange the time and place of the annual spring technical meeting follows: Arthur Notman, Chairman, F, Julius Fohs, Waldemar Lindgren.

Separates of the papers presented at the Secondary Enrichment Symposium held at the joint meeting with the American Institute of Mining and Metallurgical Engineers will shortly be sent to the members.

The American Institute of Mining and Metallurgical Engineers and the Society of Economic Geologists held a joint session in New York City, at the time of the Institute meeting, on February 19th and 20th, the Society appreciates the many courtesies extended to it by the Institute.

The majority of papers presented were an outgrowth of the Secondary Enrichment Investigation, financed by some of the larger copper companies, and carried on under the direction of Professor L. C. Graton. The meetings were well attended, some 80 men taking part in each of the three sessions. The discussion was, to say the least, lively. The papers presented follow:

Tuesday, February 19, 2 P. M. Session.—(1) Organization and Operations of the Secondary Enrichment Investigation: L. C. Grafton. (2) Rock Alteration Association with Copper Sulphide Deposits in Igneous and Schistose Rocks: Edward H. Perry, Augustus Locke, and L. C. Graton. (3) Oxidation and Enrichment at Ducktown, Tenn.: Geoffrey Gilbert. (4) Oxidation and Enrichment in Shasta County, Calif.: L. C. Graton.

Wednesday, February 20, 9:30 A. M. Session.—(1) Fundamental Conceptions of Secondary Copper Sulphide Enrichment: L. C. Graton. (2) Primary or Secondary Chalcocite? The Case for Deep Bornite Enrichment: L. C. Graton, D. H. McLaughlin, M. N. Short, and Alfred Wandke.

President Kemp presided at all the above sessions.

Wednesday, February 20, 2 P. M. Sessions.—(1) Copper Deposits in the Nikolai Greenstones, Kuskulana-Kotsina District, Alaska: Alfred Wandke. (2) The Origins of Rich Silver Ores (by title): Edson S. Bastin. (3) Habit, Etch Structure and Geological Significance of Chalcocite: Alfred Wandke. (4) Rôle of Secondary Enrichment in Genesis of Butte Chalcocite: Augustus Locke, D. A. Hall, and M. N. Short. (5) Primary Downward Changes in Ore Deposits, W. H. Emmons.

SCIENTIFIC NOTES AND NEWS

J. S. Diller, who has held an appointment as geologist on the Survey for more than forty years, retired from the Government service December 31. A luncheon was given in his honor by his associates on the Survey, at which Colonel H. C. Rizer presided.

Stephen Taber is now Acting State Geologist of South Carolina, with headquarters at Columbia.

Julian D. Sears has been appointed administrative geologist of the U. S. Geological Survey to succeed Dr. Philip S. Smith.

Philip S. Smith is in Alaska, where he is in charge of the party which will make surveys in Naval Petroleum Reserve No. 4, in northern Alaska. His party includes J. B. Mertie, Jr., Gerald FitzGerald, and R. K. Lynt.

Joseph B. Umpleby has resigned as Director of the School of Engineering Geology of the University of Oklahoma to become Vice-President of the Goldelline Oil Corporation.

R. F. Baker, of Houston, Texas, has been advanced from assistant geologist to chief geologist of the Texas Company.

Messrs. Heald, Hewett, Loughlin, Ferguson, and Hess, of the U. S. Geological Survey, will each give lectures at Johns Hopkins University during the absence of Professor Singewald.

H. Schneiderhöhn has been appointed to succeed Klockman as Professor of Mineralogy and Economic Geology in the Mining Department of the Technical High School, Aachen, Germany.

C. H. Clapp, formerly Director of the State School of Mines and Metallurgy of Montana, is now president of the University of Montana at Missoula.

T. W. Vaughan, who served for many years with the U. S. Geological Survey, has gone to La Jolla, California, to become director of the Scripps Institution.

Henry Louis, professor of mining at Armstrong College, Newcastle on Tyne, England, has been awarded the Gold Medal of the Institution of Mining Engineers in acknowledgment of the great services rendered by him to the mining profession during his thirty years of teaching.

Graham John Mitchell, chief geologist of the Cananea Consolidated Copper Co., was recently in New Haven, Conn.

G. A. Waring has completed his work in Trinidad, B. W. I., for the Whitehall Petroleum Corporation, Ltd., and is now with the Margay Oil Corporation, Tulsa, Oklahoma.

C. E. Decker is custodian for the Oklahoma Geological Survey, at Norman, Oklahoma.

H. P. Henderson, consulting engineer of New York, is doing geological work in Tonopah for the Tonopah Belmont Development Company.

J. H. Pratt has been made Director of the North Carolina Geological and Economic Survey, at Chapel, North Carolina.

John Wellington Finch has returned from a four months' stay in China.

D. G. Sinclair, formerly with the International Nickel Company of Canada, has been appointed assistant inspector of mines for Ontario, with headquarters at Sudbury.

Fred Searles, Jr., has been appointed chief geologist of the U. S. Smelting and Refining Company, and will take charge of exploration for the company's operations in the United States.

J. F. Kemp gave three lectures on geological subjects at Queen's University, Kingston, Ontario, on January 31 and February 1. A popular lecture on some of the canyons and natural bridges of southern Utah was followed by lectures on contact zones and some recent developments in the study of ore deposits.

T. L. Watson, state geologist of Virginia, was in Washington recently for conferences regarding coöperative work in Virginia.

R. T. Hill has been in Washington conferring with the chief geologist of the U. S. Geological Survey and others concerning his trans-Pecos report.

C. L. Dake, professor of geology at the Missouri School of Mines, delivered an address on the "Geology of Sand and Gravel Deposits" before the National Sand and Gravel Association at their annual meeting held in St. Louis on January 22.

The Washington Academy of Sciences held a symposium on coal at its meeting on January 17, at which ten minute talks were given by George Otis Smith, Coal, a National Issue; Charles P. Neill, Miners' Wages and Earnings; David L. Wing, Operators' Costs and Profits; H. Foster Bain, Safety and Mine Output; F. G. Tryon, Overdevelopment, its Cure; and O. P. Hood, Consumers' Economics.

At a joint meeting of the Washington Academy of Sciences with the Geological Society of Washington and the Philosophical Society of Washington, Dr. T. A. Jaggar, Director of the Hawaiian Volcano Observatory, delivered two addresses on "The Hawaiian Volcanos" and "The Tokyo Earthquake."

An Empire Mining and Metallurgical Congress is to be held in London, June 3 to 6, in connection with the British Empire Exhibition. The following organizations will participate:

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